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SEDIMENTS IN URBAN STORMWATER DRAINAGE SYSTEMS

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SEDIMENTS IN URBAN STORMWATER DRAINAGE SYSTEMS.

A. H. Roberts.

ABSTRACT.

Suspended sediment, transported in urban stormwater sewers, is examined in order to determine its source, size, mineralogy, form and surface texture characteristics. The transport history is studied in relation to the hydrological parameters of rainfall and discharge in one catchment.

The catchment is situated in North West London where field sampling was carried out over the period from March 1980 to December 1981. A Coulter Counter is used for particle size determinations; methods of sampling and the choice of dispersant and electrolyte are discussed. Particle surface texture analysis employs Scanning Electron Microscopy and preparation methods are discussed. Elemental composition is examined by energy dispersive x - ray analysis. Particle textures are described and quantified using a detailed surface area method and the Fuzzy Technique is employed in the analysis of a large number of particles.

Sediment sources in the catchment include roads, buildings, open spaces and airborne material. Sediment is washed off land surfaces during rainfall and transported along the storm sewer to the outfall. Suspended sediment sampled at the outfall is commonly in the size range 1 to 40 μm and predominantly consists of quartz particles from roadstone erosion which have undergone considerable alteration by abrasion, silica precipitation and solution during drain transport. Storms and their sediment load fall into four groups :

I. Intense rainfall of short duration generates moderately high total rainfall and discharge. Sediment comprises fresh-faced, angular, particles rapidly entrained from the land surface and of unimodal size distribution.

II. Long periods of rainfall of moderate intensity create high rainfall totals and moderately high discharge. Drain deposited aggregates and surface particles are transported first; silica precipitates develop later, leading to aggregation as the discharge falls: size distributions are bimodal.

III. Moderate rainfall and discharge transport sediment of similar characteristics to Group II but of moderated form.

IV. Low rainfall and discharge for short period transports severly altered drain sediment of bimodal size distributions.

Progressive sediment alteration along the storm sewer was simulated in a flume.

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Pages 57a, 60a, 61a, 64a, 66a and 91a have been inserted and Page 212 has been omitted.

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PART I

INTRODUCTION

AND CATCHMENT HYDROLOGY

CHAPTER I.

INTRODUCTION

1.1 Urban Storm Drainage Systems.

Following the use of combined foul and stormwater sewers of Victorian times, separate systems were developed in the 1950's to reduce the volume requiring high cost cleansing treatment. Sewer design became important with the need to remove rainfall runoff as rapidly as possible from urban surfaces to the nearest water course. The runoff at that time was considered to be clean enough for entry directly into receiving waters. One of the first methods of stormwater sewer design to be developed was the Rational Method (Lloyd-Davis, 1906) which was based on the product of the average rainfall intensity and the total impervious area of a catchment. This rather simplistic method and the time-area approach of the Transport and Road Research Laboratory Method (Watkins, 1962) dominated sewer design for approximately twenty years. The need for updating stormwater drainage design in urban catchments led to the formation in 1974 of the Department of the Environment Working Party on the Hydraulic Design of Storm Sewers. A number of studies were made which included the application of computer techniques (Colyer and Pethick, 1977). Price (1981) described drainage design and the return period of storms employing hydrological parameters and economic considerations. The final reports are collectively known as the Wallingford Procedure and offered radical new approaches to sewage design. All these reports however, omitted a most notable parameter: the sediment load.

In the recent sewer designs from the United States (SWMM, STORM and ILLUDAS, summarised in Colyer and Pethick, 1977) stormwater retention in the system is advocated. This is in distinct contrast to the previous methods described of the rapid removal of surface runoff with consequent problems of downstream flooding. Further, the runoff is becoming increasingly polluted (Natural Environment Research Council, 1975 Hall and Hockin, 1980

These studies recognise that sediment is present in storm water runoff, and that it settles out during water storage or retention, and suggest that settling ponds are included along sewers and provision made for the bulk removal of the sediment. The nature of the sediment, its source, and effects on pipe discharge however, have been largely ignored; it is this aspect of urban storm drainage which has led to the objectives of the present research.

Despite the adherence to hydrological parameters in sewer design, the presence of sediment and its effect on sewer flow are undeniable. The sediment load affects the viscosity and velocity of the discharge; sediment deposition in pipes creates friction on the pipe bed, restricts flow, and reduces the gradient and local velocity of the flow. Restrictions may lead to blockages although the design of stormwater sewers is aimed at maintaining a self-cleansing velocity (Stephenson, 1981)

Studies of stormwater quality have further indicated effects of sediment on discharge. Suspended sediment (1 to 40μm) has been shown to comprise upto 1% of thesediment load (Stephenson, 1981). Ellis (1976) and Yamada (1981) described how the fine sediment fraction is responsible for transporting toxic chemical substances; inverse correlations were found between specific chemical concentrations and particle size.

In water retention systems it has been shown that upto 90% of the sediment load may settle out during discharge (Balmforth, 1981; Wada and Suelshi, 1981; Wancelista, Yousef, Harper and Cassagnol, 1981). Water storage in the sewer system below ground is rare and is expensive both to construct and maintain. Some successful designs however, have been described by Gibbs, Alexander and Leiser (1972) and Saul and Delo (1981) in which sluices in pipes could be controlled to temporarily direct water into areas of the system which are least affected by the storm. There are no below-ground storage systems in Britain although sedimentation tanks have been constructed in motorway drains. There are many examples of surface storage of storm runoff, as for example in Milton Keynes, Buckinghamshire although these are still primarily intended to control the flow (Colyer and Pethick, 1977). The Tame system is however, actually intended to collect sediment from stormflows.

The purpose of this investigation is to examine the details of particle source and form which are essential in understanding the role of the sediment in stormwater runoff Only from appreciating the precise nature of the sediment can pollutant sources and pathways be identified and appropriate control procedures be developed.

1.2. The Study of Stormwater Sediment.

In this research the source, the nature, and changes occurring to the sediment during stormflow, are studied. The catchment in North West London, has a separate sewer system and includes a balancing pond like those described by Colyer and Pethick (1977). The sediment was studied from its sources round the catchment taking into account different types of land use; the processes and effects to the sediment of stormwater transport were examined during a wide range of rainfall conditions.

The sediment was analysed by particle size analysis, predominantly in the range of 1 to 40μm, and by using scanning electron microscopy to study the surface features of the particles. Particle size analysis methods for this size range have been well documented but scanning electron microscopy methods had to be specially adapted to analyse this sediment in three main respects. First, studies of mineral grain surface textures which apply to the bulk of the stormwater sediment, had mainly been studied in the sand size range. Account had to be taken of the effect, particularly on abrasion, of such fine grains. Second, a list had to be compiled to include all the features observed on the stormwater sediment of this urban environment, many of which did not fall into the previously described environmental based classifications. Third, previous studies have made little attempt to produce quantitative results of surface texture analyses. In order to determine as accurately as possible the surface textures of the stormwater sediment, the grain surface area occupied by each feature was estimated using an adaptation of a Fuzzy classification technique for this sediment.

The size and surface texture results, together with studies of mineralogy, gave a clear estimation of the processes of urban stormwater sediment transport.

1.3. The Aims of the Research.

The aims of the research into suspended stormwater sediment were twofold:

(i) to discover the size, appearance - shape and surface texture - mineralogy, and the form of the particles - whether they travelled individually or in conglomerations;

(ii) to discover the source of the sediment and the transport processes and pathways involved in the transport history of the sediment across the catchment and along the storm sewer.

It was the aim of the research to examine these two sets of considerations under the different rainfall and discharge conditions occurring in the catchment.

1.4. The Organisation of the Thesis.

The thesis comprises four sections the first of which provides an introduction to the field of urban stormwater research and in particular the role that sediment plays. The study catchment is described and the rainfall, discharge and sediment sampling methods are explained. The nature of the rainfall in the catchment is then described and the storms and the discharge they generate are classified into four main groups. The classification forms the basis of the sediment studies of Sections II and III in which particle characteristics are related to variations in rainfall and discharge. Particle size analysis and scanning electron microscopy are divided into Sections II and III respectively because of the widely differing techniques involved and because of the quite distinct forms of the results. The results do however compliment each other and a full picture of the sediment transport history is given in the concluding Section IV, based on the combined results of hydrology, particle size and surface texture analyses.

CHAPTER 2

CATCHMENT DESCRIPTION AND SAMPLING SCHEME

2.1. Catchment Situation and Land Use.

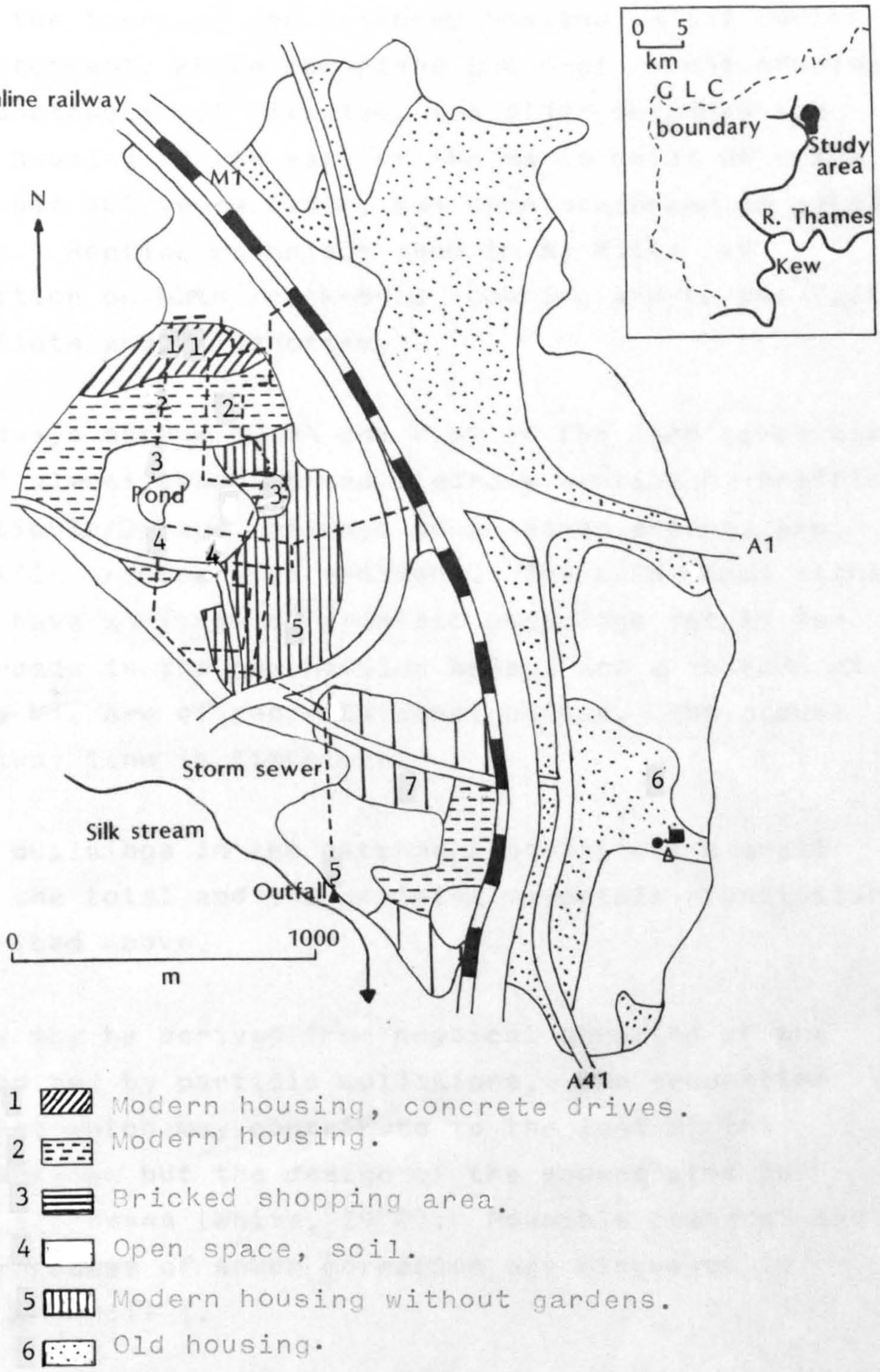
The study catchment is situated in the outer metropolitan district of North West London, approximately 14km from the city centre. Covering an area of 420ha, the catchment supports a mixed land use which is served by a separate sewer system as shown in Figure 2.1. The catchment was developed to its present form in the 1970's and previously had been open land, including an airfield, belonging to the Ministry of Defence. The catchment is now a residential area with central schools, retail and office facilities. The south of the catchment is an area of light industry, warehouses, offices and military and police headquarters. The southern limit of the M1 motorway and the mainline railway from Euston Station traverse the catchment in a north-south section. To the east of the motorway is a housing area, dating from Victorian and inter-war periods, where large gardens are common. A detailed breakdown of the land use is given in Table 2.1.

Although Table 2.1 shows "open land" as being the largest single land use type, this in no way negates the overall urban nature of the catchment. The open space land includes a grassed area around the balancing ponds which serves as an amenity for the local dense housing without gardens. Of the open space area 11.5% is occupied by the Royal Air Force Museum and its grounds and the remainder is accounted for by school playing fields and municipal sports grounds. As these grassed areas are heavily trampled they are largely impermeable to runoff and thus constitute a semi-pervious surface.

The age and type of housing building materials, which are important for their sediment contribution to runoff, vary across the catchment. The flats and maisonettes of the central

FIGURE 2.1.

STUDY CATCHMENT SHOWING: LAND USE, STORMWATER SEWER, INSTRUMENTATION AND SAMPLING POINTS.



Land use class.

1 Modern housing, concrete drives.

2 Modern housing.

3 Bricked shopping area.

4 Open space, soil.

5 Modern housing without gardens.

6 Old housing.

7 Commercial traffic, Aerodrome Road.

Instrumentation

■ Bulk roof sampler.

● Rain gauge.

▲ Discharge monitor and water sampler.

Δ Air impactor sampler.

1- 5 Sewer sample points.

1- 7 Sample points in land use areas 1-7.

area have a relatively high proportion of concrete in their make up while the terraced and detached housing in the northern part of the catchment, which comprises the most recent housing, is of brick construction. Likewise, the older detached and semi-detached housing to the east of the M1 is built of brick but, being almost 100 years older, has been weathered to a much greater degree. Roofing materials tend to be tiles of clay composition on both brick-built housing and on the flat roofs of the flats and maisonettes.

Roads and railways occupy 12.5% and 2.5% of the land respectively. As a result of almost constant and vigorous erosion by traffic the roads particularly, and railways to a lesser extent, are the most prolific producers of sediment. The main roads within the catchment have surfaces of granitic chippings set in tar but the side roads in the new housing areas, and a section at the end of the M1, are of concrete construction. The gravel along the railway line is limestone.

The remaining buildings in the catchment constitute a small percentage of the total and the building materials are similar to those described above.

Some particles may be derived from physical abrasion of the sewer walls and bed by particle collisions. The proportion of such sediment which may contribute to the load of the discharge is unknown but the design of the sewers aims to minimise such processes (White, 1970). Possible chemical and biochemical processes of sewer corrosion are discussed in Chapter 3 and Appendix 1.

2.2. The Topography and Rainfall Regime of the Catchment

The catchment covers 3km from north to south and slopes, with a mainly uniform gradient, from 90m at the head of the catchment to 40km at the outfall.

TABLE 2.1

PERCENTAGE-AREA OF LAND USE TYPES

Land Use Types	Percentage Area Occupied
Open land	40
Housing	35
Roads and railways	15
Schools and public buildings	5
Warehouses, depots and yards	3
Shops and offices	2

Data supplied by the Meteorological Office for the Hadley Road Pumping Station, situated 12km north east of the study catchment, give an average annual rainfall total of 646mm based on the 30 year period from 1941 to 1970 and an annual average of 733mm over the 5 years covering the sampling period from 1977 to 1981 (Table 2.2). The average monthly rainfall totals for the catchment over the study period are given in Table 2.2., the missing values occur in months when a few days monitoring were overlooked during holiday periods. The table shows the usual irregular pattern of actual monthly rainfall which commonly ranges from less than 50% to more than 150% of the average in successive months. The annual totals between 1977 and 1981, are, however, less varied and range from 634 to 814mm, a difference of 30% overall. During the research period the monthly averages for the period from 1977 to 1981 were generally similar to, or fell between, the catchment values. The exceptions were January and November of both years, 1980 and 1981, when the catchment was drier although no significant reason has been found for this. As described in Chapter 3, seasonal rainfall variation appears to have no noticeable effect on the major rainfall characteristics of the catchment.

2.3. The Storm Sewer System.

The separate sewer system for the stormwater runoff which was studied in this catchment is shown on Figure 2.1. The length of drain studied was approximately 1740m from the head of the catchment to the outfall. The details of the pipe size, gradient and length of straight stretches of pipe between sample points 1 to 5 are shown in Table 2.3. Manholes occur at regular intervals of 150m on straight stretches and at changes in direction. Changes in direction are less than 45° and do not significantly affect the velocity of the flow in the drain(White, 1970). The sediment sampling points are distributed between the head of the catchment and the settling pond, upstream and downstream of the pond and at the outfall,as described in Section 2.5. A relatively large pipe (42") at a low gradient (1 in 950) feeds into the settling pond whereas a smaller pipe (21") with a higher gradient (1 in 50) drains the pond. The pond has a ramp on one side for the excavation of the sediment. Pipe size is increased (60") for combined flow with the adjoining sewer. Further downstream a second main sewer runs in parallell and both simultaneously enter the receiving stream at the outfall culvert.

2.4. Stormwater and Sediment Monitoring.

2.4.1 Rainfall Records.

Rainfall was recorded daily by an automatic syphon rain gauge sited on the flat roof of a three-storey building approximately 1km north of the culvert. Thirty storms were monitored during the research period. The inaccuracies of rainfall measurement as a result of local wind currents around the rain gauge, and its optimum positioning in conditions of uniform fetch, have been well documented in Robinson and Rodda (1969) and Ward (1975). In this case the height of the building exposes the gauge to relatively strong wind currents which are made irregular by the configuration of the protruding roof-door. The distance of 1km between the rain gauge and the culvert, may be sufficient on some occasions to allow differences in the rainfall. Colyer (1981) has shown that observations from a single rain gauge may be misrepresentative of individual storms over an urban catchment as small as 150 hectares. If this situation can occur in the catchment being studied here ideally a much tighter network of at least three rain gauges should be used. The storm drain collects runoff from the entire catchment therefore the discharge reaching the culvert could have originated upto 3km away. Unfortunately additional rain gauges originally sited within the catchment had to be withdrawn as a result of constant vandalism. However, satisfactory results of rainfall were obtained on a monthly basis as shown by comparison with local Meteorological Office

TABLE 2.2

AVERAGE MONTHLY RAINFALL TOTALS OVER 5 YEARS, JANUARY TO DECEMBER 1981

	Meteorological Office Data Average Monthly Totals, mm.					5 Year average, mm	Catchment Data Average Monthly Totals, mm	
	1977	1978	1979	1980	1981		1980	1981
January	63.1	95.3	78.3	30.5	33.4	60.1	23.4	20.1
February	86.3	43.5	55.6	42.7	16.8	49.0	41.9	5.8
March	67.0	72.0	109.7	70.1	106.6	85.1	49.7	101.6
April	35.4	45.9	86.2	31.9	48.0	49.5		33.8
May	35.1	62.4	138.1	20.8	87.4	68.8	31.2	71.9
June	76.2	75.0	27.6	68.2	35.1	56.4	74.2	21.2
July	17.7	63.9	23.9	88.1	88.0	56.3	58.7	45.7
August	132.4	41.9	68.3	44.9	41.6	65.8	41.4	
September	21.1	22.7	22.9	29.6	119.6	43.2	33.0	98.0
October	104.6	42.6	8.4	63.1	97.7	63.1	104.6	62.2
November	98.6	65.3	22.3	42.6	37.4	53.0	26.2	38.1
December	75.9	64.3	137.2	101.9	33.3	82.5		
Annual Total	813.6	693.6	778.8	633.6	745.2			

TABLE 2.3.

PIPE SIZE, GRADIENT AND LENGTH OF STRAIGHT STRETCHES BETWEEN CHANGES IN DIRECTION ACROSS THE CATCHMENT.

Position relative to Sample points 1-5	Pipe, Inches	Gradient	Length, m
Head of catchment 1 to 2	42	1 in 950	220
2 to 3	42	1 in 950	180
Above pond 3 to pond	42	1 in 950	25
Pond to below pond 4	21	1 in 50	50
Downstream of 4	30 42	1 in 83 1 in 560	165 465
Adjoining sewer	60	1 in 420	205
Two sewers lying parallel	51 51 63 63	1 in 350 1 in 350 1 in 520 1 in 520	280 280 150 150
Outfall, 5			

data. Further, individual storm data was sufficiently accurate to help understand sediment entrainment and transport in runoff.

The rain gauge was accurate to fifteen-minute intervals. The rainfall totals (in millimetres) the intensity (millimetres per hour) and the storm duration (hours) were calculated for each storm and the results are given in Chapter 3.

2.4.2. Discharge Monitoring.

The gauge height in the stormwater culvert was measured by an Arkon water stage height recorder. The instrument was housed directly above the culvert. The recorder operates from compressed air and provides continuous values over the range of 0 to 100 inches (2540mm)for at least one week, depending on the air supply. The values are accurate to within 2 inches (50.9mm) although at exceptionally high flows, on two occasions, the range was exceeded. Instantaneous velocity readings were made, over the range of gauge heights, using an Ott current meter. The cross-sectional area of the culvert for a range of water depths, was calculated from the gauge height and the known dimensions of the culvert; multiplied by the velocity, this provided point discharge readings. From the plot of the discharge points against the gauge height, a straight line rating curve was constructed (Figure 2.2) from which all intermediate discharge values could be read from 0 to 1000 cumecs. The accuracy of the rating curve was determined by the degree of deviation of points from the line; the correlation coefficient was high at 0.997. The equation of the line is:

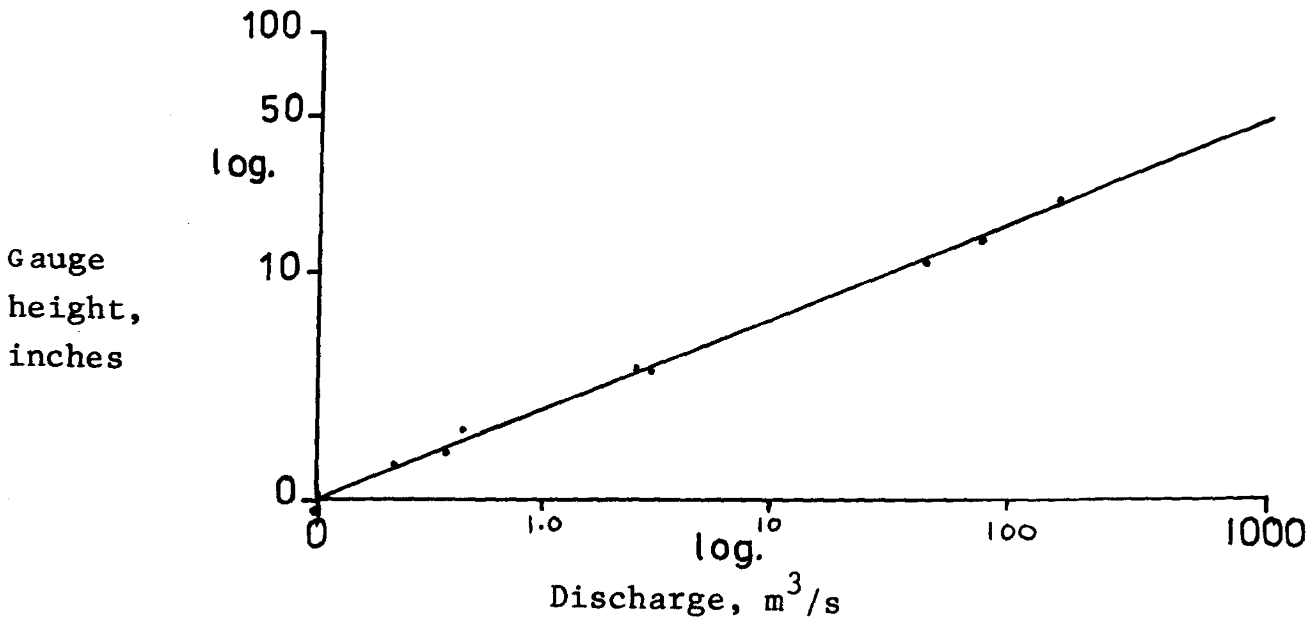
Equation 2.1.

$$\log y = 0.439 + 0.403 \log x.$$

The discharge was measured during twenty-two of the thirty storms studied for their hydrological and sediment characteristics.

FIGURE 2.2

DISCHARGE RATING CURVE FOR OUTFALL CULVERT.



For the remaining eight storms the discharge data were unreliable due to the mal-function of the gauge height recorder. The results are presented in Chapter 3 in terms of discharge peak, discharge duration, time to peak and the form of the hydrograph. The results are sufficiently accurate to be closely related to fluctuations in rainfall totals and intensity and sediment load throughout the storms.

2.4.3. Sediment Sampling.

The sediment load in the discharge of storms was monitored over the period of twenty two months from March 1980 to December 1981. Samples of approximately 500ml were taken using a Rock and Taylor 48 bottle automatic pump sampler. The sampler was battery-operated and housed, with the discharge monitoring equipment, above the culvert (Plate 1). The sample intake was a stainless steel nozzle (20mm diameter) fixed to the bed of the culvert, as shown on Figure 2.3. At eight-minute intervals, samples were pumped up from the culvert to the collection bottles through a 8mm diameter plastic pipe leading from the intake nozzle.

The aim of this study was to examine the suspended fraction of the sediment load. Although the flow is turbulent some stratification of the load does occur during high flows and the depth through which the suspended sediment is distributed varies with the total depth of the discharge. To ensure representative sampling in these circumstances, the problems involved in having the sample intake for suspended sediment in a fixed position on the channel bed, were carefully considered. Ideally suspended sediment flux profiles should be determined to identify variations through the flow,however, it can be assumed that maximum flux values occur close to the bed (Bolton, 1983). Bagnold (1937) however, distinguished suspended load from bed load simply as the bed load being that portion of the total load whose immersed weight is carried by the

'LATE 1.

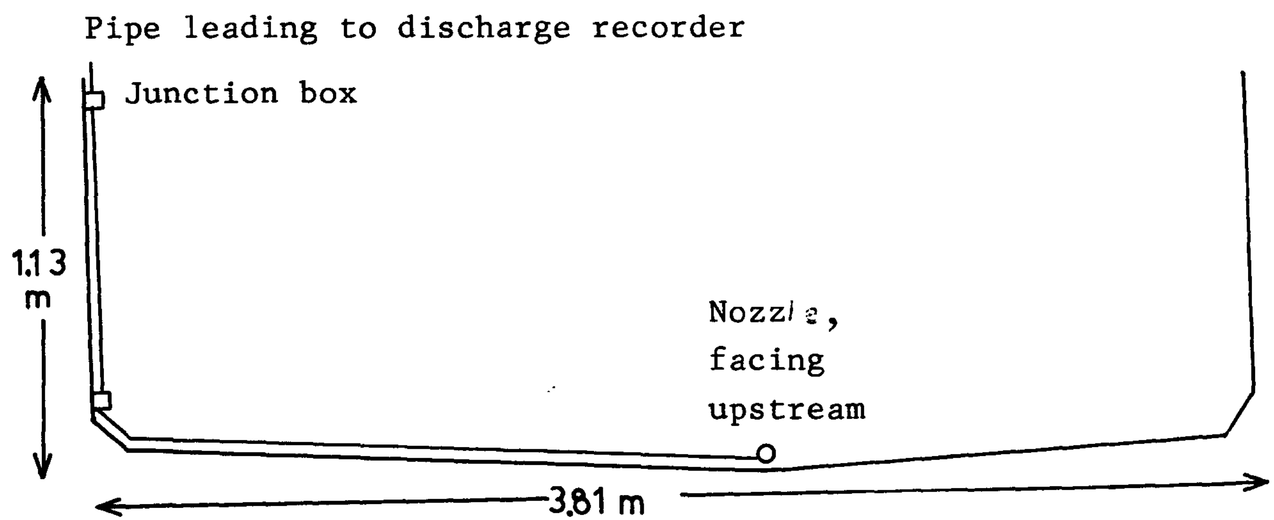
THE STORM SEWER OUTFALL.

The storm sewer outfall with instrumentation housed behind railings (above left of culvert, facing). Sample intake pipe leads from instrumentation down culvert wall and mid-way across culvert floor.

Immediately after heavy rainfall the stormwater can be clearly seen merging with the Silk Stream, flowing from left to right of picture.

FIGURE 2.3.

CROSS SECTION OF THE OUTFALL CULVERT WITH THE POSITIONS OF THE INTAKE NOZZLE AND PIPE.



fluid. As mentioned above, the nozzle is in a fixed position in relation to the changing discharge and sediment size and concentration, both within and between storms. The upper particle size of the intake is limited by the nozzle size and therefore a representative size range for all suspended sediment cannot be obtained. In addition, the nozzle itself can induce eddies in the flow which tend to discourage particles from immediate entry. In exceptionally high flows, negative fall velocities unavoidably occur as a result of the difference between the ambie nt flow velocity and the lower sampler intake velocity. Although this certainly affects larger particles, it appears to have little influence on particles less than 1000µm (Bolton, 1983).

The problem of the fixed position has been widely discussed (for example, Marsalek, 1983) but no suitable alternative has been found. The nozzle size and position for this culvert was chosen to accommodate the modal range of sediment carried by storms in this catchment.

The 8mm diameter of the piping has been suggested to be the optimum diameter to overcome cohesive forces both within the water and between the water and the pipe. It is not wide enough however, to allow the flow to fall back down the tube under gravity but does provide a simple flushing mechanism and the sampler has a primary routine which allows the initial sample to clean the system then run to waste.

Despite the disadvantages, the system was found to be satisfactory for this study. Sediment sizes in the range of 1 to 40µm were consistently measured from the majority of storms but this was not restricted by the instrumentation as shown by the sampling of sediment upto 90µm in high discharges and 30µm at maximum in low flows; particle sizes of up to 1000µm have been captured with this system (Ellis, 1979; Bolton, 1983).

Sampling was initiated when the discharge in the culvert rose between 50 and 60mm above the baseflow thus operating the float switch. The sampling process is then repeated, filling successive sample bottles at 8 minute intervals. The sampling procedure ends either when the float switch is disconnected by the falling of the water level or when all the 48 samples have been taken. The time interval was chosen to allow sufficient time for the sample to be taken and to provide the maximum sampling time through storms.

The full sampling time period of 6.4 hours suits the majority of storms well. There are however a number of short storms (0.2 to 2.5 hours) for which the samples are too widely spaced to capture the details of the initial high discharge, as can be seen from the gauge height record. Occasionally, storms of long duration cause the discharge period to exceed the sampling time by up to three hours. However, from the gauge height record it can be seen that by this time the discharge is falling gradually and no further fluctuations occur. A further problem arises in separating successive storms which occur within the maximum sampling time. The sampler does not distinguish between storms and thus a continuous set of samples can include a few separate storms.

Analysis of the turbidity and the sediment concentration of the samples may indicate the difference between the two storms or a distinction may be made from a study of the hydrograph. The problem of attaching samples to specific points in the hydrograph lies in not knowing exactly when sampling was initiated. This depends on flow conditions with the disadvantage that such details as the type of sediment associated with peak discharge cannot be established accurately.

The samples were collected as soon as possible after a storm because algal flocs tend to develop rapidly, incorporating sediment, particularly if the temperature in the sample bottles is high enough (as discussed in Chapter 3). The growth of algae is also a problem in the piping, especially in the summer. The piping is semi-transparent and the light and warmth encourage growths which tend to trap the sediment taken up and to block the pipe. Occasional flushing helped to keep the pipe clear.

2.5. The Sampling of Sediment Throughout the Catchment

2.5.1. Major Sources of Sediment.

The major sources of sediment in the catchment appeared to be: the air, buildings and roads. During rainfall airborne particles are washed out of the atmosphere onto buildings, and thence to roads, or directly onto road surfaces. The sediment joins that washed off roofs, buildings and the road surface, and the runoff is fed via gutters into the storm sewer.

Airborne particles were collected by a vacuum impactor sited at the first floor level of a building in the catchment (Figure 2.1). The position of the sampler suffered from eddies in the air currents which are set up around the buildings but this applies throughout the catchment and as such representative samples are obtained. Care is needed when handling the filters on which the particles have been collected. The particles are collected dry and adhere only loosely to the sample filter.

Weathered roof building material was sampled in runoff which was collected in a tipping bucket attached to the downspout from a house roof gutter. The house used was approximately forty years old and of pitched tiled, roof construction.

A number of further samples were collected in road gutters in different areas of land use around the catchment as is described below.

Lastly, a selection of stormwater sediment samples were taken and are here considered as the source of the altered particles characteristic of urban runoff and sewer transport.

Particle analyses of source and drain sediment are given in Chapters 6 and 7.

2.5.2 Land Use Sediment Sampling

Samples were collected across the catchment in the different areas of land use listed in Table 2.4 and delineated in Figure 2.1. In each area samples were taken directly upstream of the lip of a road drain, where stormwater was flowing into that drain and where the depth of flow was sufficient for sampling. A 20ml pipette of 1mm nozzle diameter was used and five samples were bulked to make up the required volume for size and surface texture analysis. The catchment sampling was completed during one storm. To ensure the samples were as representative as possible of the land use, the samples were taken near the centre of the area thus minimising the inclusion of sediment from surrounding areas.

The areas of housing were divided on the basis of their age and building materials; the area of shops and offices, the main road with depots, and the open spaces, formed the remaining three classes. The land use classes are listed as nearly as possible, in their order down the catchment, and are discussed further in Chapter 7.

2.5.3 Samples Taken Along the Storm Drain.

Samples were taken at intervals along the stormwater sewer to establish the size and surface texture characteristics

TABLE 2.4

LAND USE SAMPLE POINTS.

Land Use Areas	
1	Modern housing, concrete drives
2	Modern housing
3	Bricked shopping area
4	Open space, soil
5	Modern housing, without gardens
6	Old housing
7	Commercial traffic, Aerodrome Road

TABLE 2.5

STORM DRAIN SAMPLE POINTS

Sample point	Position
1	Head of catchment
2	Midway between samples 1 and 3
3	Immediately upstream of settling pond
4	50m downstream ofsettling pond
5	Outfall culvert

of the sediment and the processes of alteration which occur with increasing residence times and distances of travel.

The sampling points were determined by the desirability of establishing: the nature of the sediment at the head of the catchment and at the outfall, the influence of the settling pond, and any intermediate changes. The sample points are listed in Table 2.5 and shown in relation to land use in Figure 2.1.

Grab, hand samples were taken using a wide-necked container held within 5mm of the channel bed in order to obtain the most representative suspended sediment.

CHAPTER 3

THE HYDROLOGICAL CHARACTERISTICS OF THE STUDY CATCHMENT

3.1. The Hydrological Characteristics of the Catchment.

The patterns of rainfall totals and peak discharges for the region of the study catchment have been described in Chapter 2. The hydrological characteristics influence the size and surface texture of the sediment transported in the stormwater. It is therefore relevant to discuss in this chapter, features of individual storms in terms of the dominant rainfall totals and intensities, peak discharges, typical response times and antecedent conditions as they affect the sediment. Continuous readings were made of rainfall totals and discharge at the drain outfall for the thirty storms monitored.

Table 3.1. shows the ranges and predominant values of the major hydrological characteristics and those resulting from initially high rainfall intensities above the minimum value measured of 2.8 mm/hour. Rainfall totals are largely in the range 4 to 9mm and generally determine the magnitude of the discharge. However, with the occurrence of high total rainfall, intensity becomes the stronger influence on discharge volume and the pattern of flow rates through the storm, as described in Section 3.3.3.

The discharge throughout each storm was calculated from the flow level data employing the rating curve and the technique is described in Chapter 2. The total discharge was calculated by integrating the area under the hydrograph. The discharge duration was measured as the time from a rise in drain-flow at the outfall of 50 to 60mm above base level, when the sampler became operative, to the return of the discharge to base level (Ackers, White, Perkins and Harrison, 1978). Peak discharge values are predominantly

TABLE 3.1.

RANGES AND MODAL VALUES OF HYDROLOGICAL CHARACTERISTICS

	Rainfall Total mm	Rainfall Intensity mm/hr	Rainfall Duration hr	Discharge Total cumecs	Discharge Peak cumecs	Discharge Duration hr	Lag Time hr	Time To Peak Discharge hr
Total Range	1.0-19.1	0.2-20.4	0.25-8.5	7.1-81.9	3.3-31.5	1.25-9.0	0.75-7.0	0.7-3.6
Modal Values	4.0-9.0	0.8- 2.0	1.0 -8.5	4.0-22.0	3.5-13.0	2.0-9.0	0.75-7.0	0.7-3.6
Initial Values in storms		2.8-5.0	0.0-0.5		4.0 - 31.5	0.25-0.5	0.5-1.5	0.0-0.5

within the range 3.5 to 13.0 cumecs and typically occur in rapid response to the rainfall. The lag periods, of between 0.75 hours and 7 hours, were measured from the beginning of the rainfall to the onset of the storm discharge when the water level in the drain had risen 50mm above the baseflow (Ackers, White, Perkins and Harrison, 1978).

As described in Chapter 2, the runoff from an urban catchment can be rapid or may be detained with time periods to peak discharge of between 0.7 hours and 3.6 hours for the storms monitored. Open spaces and grassed areas are included in the impermeable area contributing to runoff as surfaces are severely compacted by constant trampling. Drainflow is efficient in transporting runoff from the surface and through the system. Additional evidence for the removal of a very
high proportion of the total rainfall is the
high positive correlation between the duration of the rainfall and the time to peak discharge (see Figure 3.1. (vii)) in storms of high intensity rainfall and to a lesser extent for lower intensity storms. However, it has been reported that water losses within urban catchments average from 20 to 30% and include evaporation, absorption, infiltration and at least temporary detention within the drain network (Ellis, and Harrop, 1984; Van der Ven, 1984).

As the catchment is largely impermeable to runoff, there is no seasonal antecedent storage effect on the discharge regime. The only discernible seasonal influence is the predominant occurrence of storms of initially high rainfall intensity during the summer months of May to September and a discharge response following a closely similar pattern.

3.2. The Hydrological Control of Storm Sediment Characteristics

3.2.1 Rainfall and Discharge.

The hydrological response of a sewer system has a significant

FIGURE 3.1.

CORRELATIONS OF HYDROLOGICAL PARAMETERS

FOR STORM GROUPS I - IV.

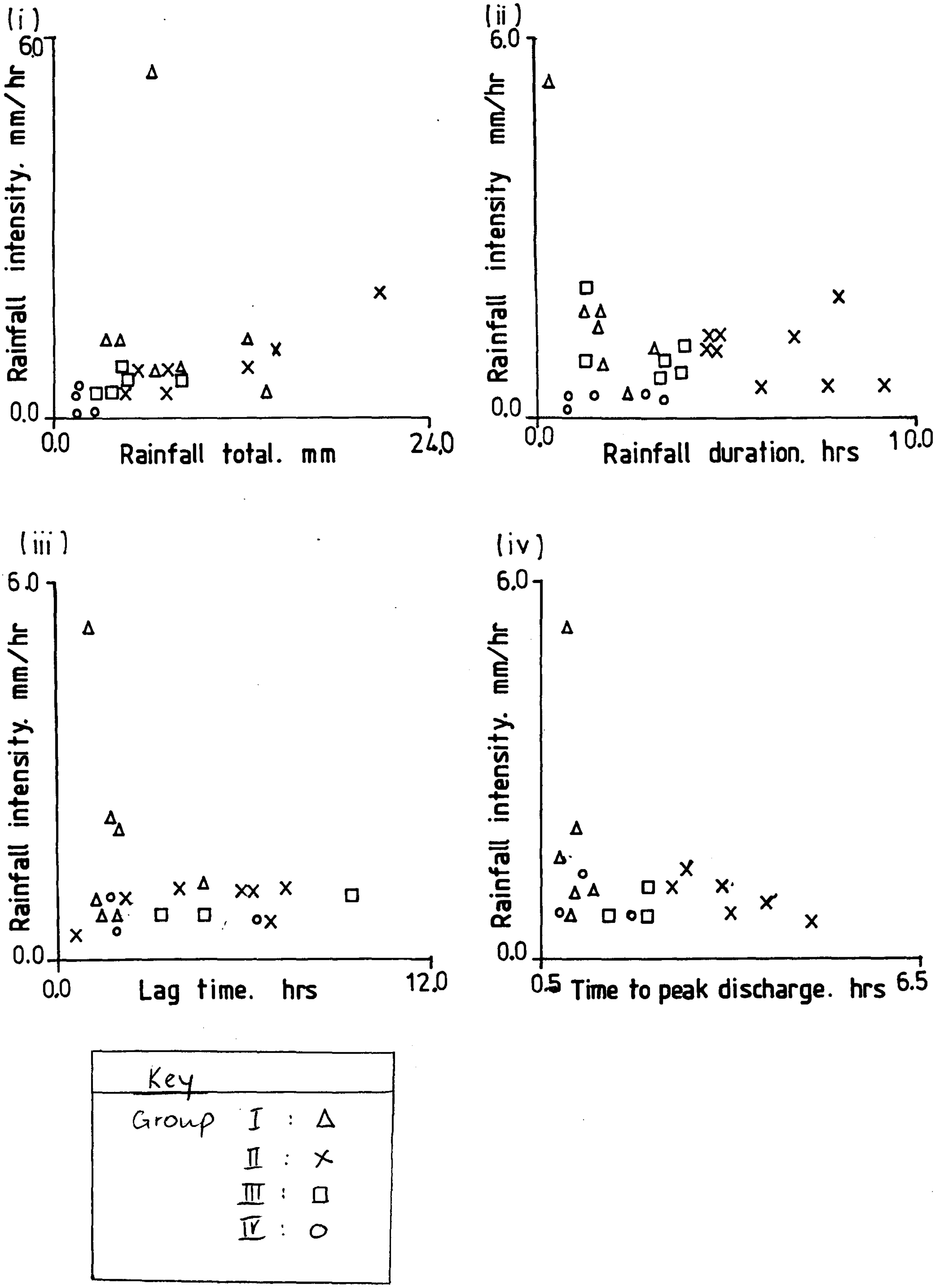
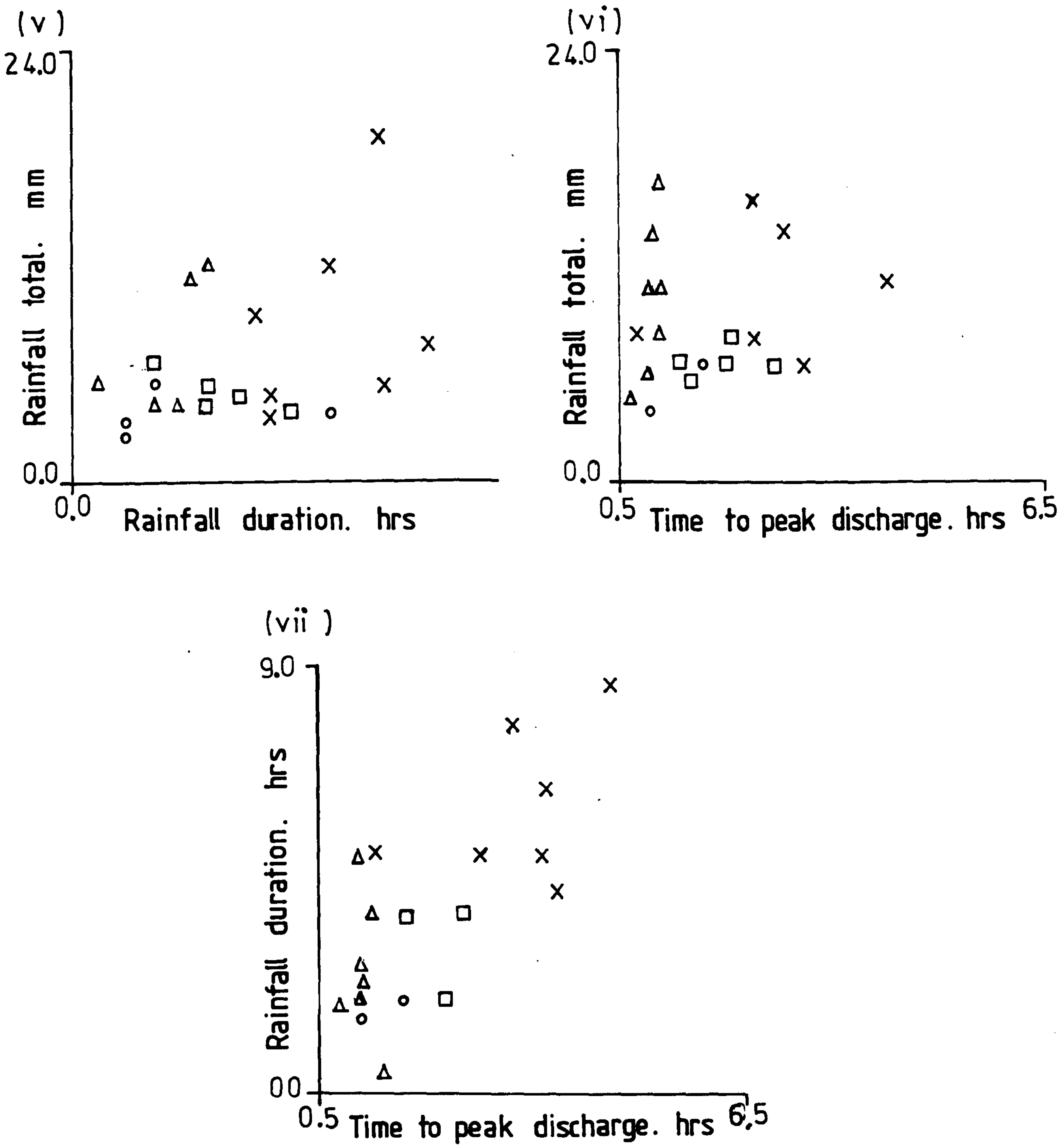


FIGURE 3.1. (continued)



influence on the size and surface texture of the sediment transported. While several authors, for example Statham (1977), have hinted at the relationships between discharge and sediment size, few detailed studies have been reported and no examination at all has been made of surface textures created during storm sewer discharge.

The availability of sediment is the limiting factor on the quantity and particle size of sediment which can be entrained in runoff. The sediment availability is primarily controlled by the antecedent conditions as described below. Providing that sediment is available, the roughness and extent of the crevices in the road surface influences which sediment is entrained (Gutt and Nixon, 1972; Neville, 1974), as described in Chapter 7. However, this is a constant factor for all the storms studied in the catchment (Sartor and Boyd, 1972). The quantity and size of the sediment entrained in runoff then depends on the intensity of the rainfall; sediment is moved once the depth of flow is sufficient to overcome the surface roughness (Ellis, in Press). The sediment entrained initially includes both that deposited by the previous recessional discharge, and that which has accumulated on the surface between storms. The discharge, and hence the capacity of the drainflow to entrain and transport the sediment, depends on the rainfall intensity and total and on the storm duration.

The specific entrainment values of rainfall intensity and total, and of discharge for particle size ranges can be gauged from a comparison of the sediment size ranges sampled during storms of varying discharge. The upper limit is restricted by the size of the sediment sampling nozzle. The storms of the lowest discharges recorded (peak 5 to 13 cumecs, duration 1.5 to 3.0 hours, Group II, Table 3.2) entrain almost no surface material but are able to transport drain deposits as shown in Chapter 5. From Chapter 5 it can be seen that a rainfall intensity of at least 0.8mm/hour is required to entrain individual surface particles of 1 to 3μm (Group III storms, see below) and generate sufficient discharge to transport them to the sampler at the outfall. The exact intensity required depends on the previous degree of wetness of the catchment and this value necessarily only refers to this catchment and its conditions of absorption and water loss.

3.2.2. Antecedent Conditions.

The period of time between storms and the hydrological characteristics of the preceding storm, influence the size and the surface textures of the sediment transported in runoff and drainflow. The antecedent dry period was measured in hours from the daily rainfall records from the end of one storm to the onset of the next. Small showers of rainfall intensities of less than 5mm per hour for half an hour of less created insufficient discharge to activate the sampler but their possible effect on sediment transport is considered. During dry periods surface sediment is accumulated and is available for transport by subsequent runoff. Dry intervals during the study period of January 1980 to Decenber 1981 were most frequently less than 150 hours (approximately 7 days) in this catchment. However, only the few periods of more than 150 hours appear to be long enough to accumulate sufficient sediment to have any influence on the sediment size distributions.

The second aspect of antecedent conditions is the nature of the preceding storm. From the rainfall total and intensity and discharge of the antecedent storm, irrespective of the length of the intervening dry period, the probable size and surface textures of sediment deposited in the drain by the receding discharge can be assessed. The assessment is based on the comparative storm study and classification shown below and is therefore particularly useful in the prediction of sediment characteristics of a preceding storm for which rainfall and discharge data alone are available.

The length of antecedent dry periods is an independent parameter and cannot be related to rainfall parameters. The storms have been classified into four major groups according to their rainfall characteristics (Section 3.3.). Antecedent dry periods do not conform to these groupings but do help to explain the relationships between particle size and hydrological characteristics particularly when the periods are either extremely short, where very little sediment has accumulated, or extremely long, when a considerable quantity of sediment is available for entrainment. Details are described in Chapter 5 and the relationships between particle size and antecedent conditions can be seen in Figures 3.1 (iii) and 3.1 (v).

3.2.3. The Influence of Organic Matter on Particle Aggregation.

In addition to physical hydrological controls, water chemistry also influences sediment characteristics. The presence of organic matter and silica in solution are two major factors dependent on water chemistry which greatly effect the form of the sediment.

It has been shown by Ellis (1979) that between 20 and 30% of the total dry weight of the load transported by stormwater are made up of organic material. The organic material includes plant debris, pollen grains and single celled animals such as diatoms, plankton, algae and fungi. Once this material has been degraded, it can constitute 30 to 60% of the organic carbon content found in the stormwater. Filamentous algae form slime mats rooted to the bed of the storm drain and entrap fine inorganic particles which are deposited by the falling discharge (Ellis, Hamilton and Roberts, 1982). The inorganic particles are subsequently re-entrained by the flow of the following storm and may be transported with organic material as silica cemented aggregates or as flocs with a high concentration of inorganic particles (Swift, Schubel and Sheldon, 1972; Krank, 1975; and Guy, 1967). Ellis (1979) has suggested that fine inorganic particles become readily attracted to, and coated by, the organic material.

The processes appear to be particularly active where a high concentration of sulphur-reducing bacteria are present in the slimes and where there is an oxygen deficiency (Arnold, 1985).

It is postulated therefore, that the inorganic sediment is transported in flocs, with organic material, which can include suspended particles of all sizes. The situation is not entirely clear since there are a number of ions in solution, and electrostatic charges, which may enhance attraction or dispersion between the fine particles of 1 to 40µm, under discussion (Guy, 1976)

The aim of this study is to examine the characteristics of the inorganic particles. To determine the natural form of the sediment in the flow, and to determine any adverse effects of the sampling equipment, a large grab sample was analysed directly from the flow during moderate discharge. The sediment was in the form of aggregates, with loosely adhering particles and separate individual particles, covering the size range of 1 to 40µm. Any slimes have been removed by previous discharge. Samples were however left to stand for 24 and 36 hours by which time extensive algal growth had developed, especially in conditions of heat and light, and progressively incorporated the particles into flocs. The full details of the processes of alteration during different conditions of storage are given in Appendix 3.

The pretreatment (Chapter 4) in intended to remove organic material. The addition of sodium azide is to kill any flocculation algae present, and prevent any further growth. Dispersion by the ultrasonic bath and sodium pyrophosphate was to break up any flocs, leaving the silica-cemented aggregates and individual particles free for examination.

The remains of flocculated organic material are not visible with the scanning electron microscope as they are either disseminated or appear translucent through the microscope. Only organic material which is not destroyed by the pre-treatment can be observed with the microscope, for example, the cell structure of plant material, fibrous forms, diatom tests and pollen grains. The vast majority of the particles are quartz with silica coating and often aggregated which is confirmed by energy dispersive x-ray analysis. The silica-cemented aggregates are stable and may be transported alone or within larger flocs but this cannot be determined from the study of the inorganic particles alone.

In the presence of a high organic matter content, anaerobic environment and alkaline pH values, sulphur-reducing bacteria have been seen to oxidise sulphur to hydrogen sulphide which has a corrosive effect on the concrete of the sewer wall (Arnold, 1985). The rate of corrosion depends on the type of concrete and has been shown to range from negligible to strong with 0.5 to 8% average weight loss over 270 days (Sand+Bock(1984).
The nature of the drain concrete under discussion here is not known and no mention is made in the literature of whether, or how, the corrosion affects the contribution of sediment from the sewer walls to the load of the discharge. It is however, a probable and continual source of sediment although the proportion of the sediment load is unknown.

3.2.4. The Influence of Silica Precipitation on Particle Aggregation.

In addition to physical hydrological controls, water chemistry also influences sediment characteristics. In natural streams several authors have noted the aggregation of suspended sediment (Krank, 1975). In this urban environment high concentrations of silica in solution have been identified as important in aggregating particles (shown in photomicrographs, Chapter 7).

Silica in solution derives most commonly from the weathering of rock-forming minerals to detrital alumino-silicates in soils (Paton, 1978). From there it is washed out into receiving water courses in an amorphous form (Lerman, 1979). In urban areas the weathering and erosion of concrete is a common source of silica particularly where it contains siliceous material such as chert or chalcedony (Palmer, 1977; Shirley, 1981). In addition, where diatoms occur in water the breakdown of the siliceous tests is another very likely source of silica (Lerman, 1979). Diatoms have been recognised from photomicrographs of surface stormwater samples in this study (Plate 3.1.) and the high silica content shown by energy dispersive x-ray techniques (EDXA) (Plate 3.2.). As well as silica-rich waters the diatoms need light to survive (Black, 1973) which is absent within the drainage system. The occurrence of accumulated and broken tests (Plates 3.3 and 3.4) signifies the death of the diatoms in the drain and the subsequent breakdown of the tests releases further silica into the system.

The solubility of silica is both temperature and pH dependent. Solubility increases from 100ppm at 25°C to 300ppm at 100°C (Krauskopf, 1959; Lerman, 1979), Appendix Figure 1a.). From pH 4 to pH 6 silica solubility is low and unaffected by pH variations in this range. Silica in the form of quartz becomes more soluble in acid conditions of pH 4 to pH 7 with hydrogen ion attack (Loughman, 1969)(Appendix Figure 1b.). Further details of silica solubility are shown in Appendix 1. Typical values of temperature and pH found in the stormwater runoff are 16°C and pH8.

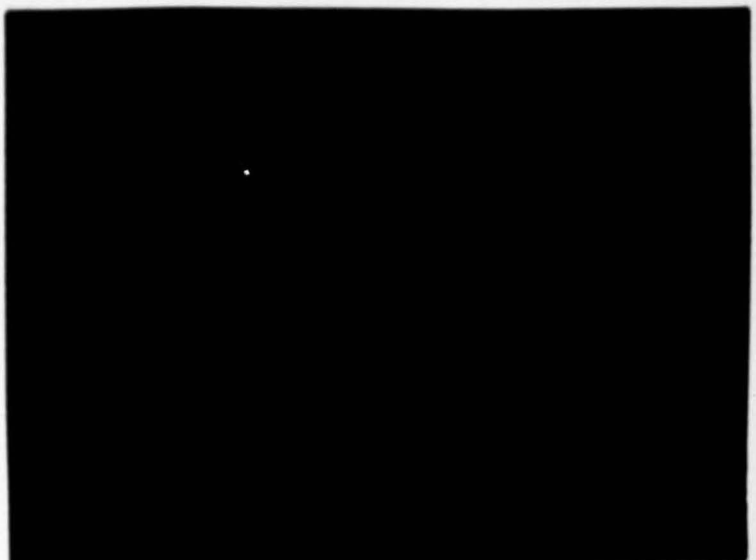
Silica precipitation has been seen to occur preferentially on fine particles of less than 2µm in the suspended clay size fractions of deep-sea and near-shore lake sediments (Gees, 1969; Iler, 1975; Lerman, 1979). In the suspended stormwater sediments three aspects of silica precipitation are recognised. Precipitation on individual particles or over groups of particles occurs in two forms. One form is of

PLATES ILLUSTRATING THE PRESENCE OF SILICA IN STORMWATER SEDIMENT SAMPLES.

PLATE 1 x 6100

Siliceous Diatom (McCrone, 1973-1980), length: 15µm, maximum width, 4µm.

PLATE 2

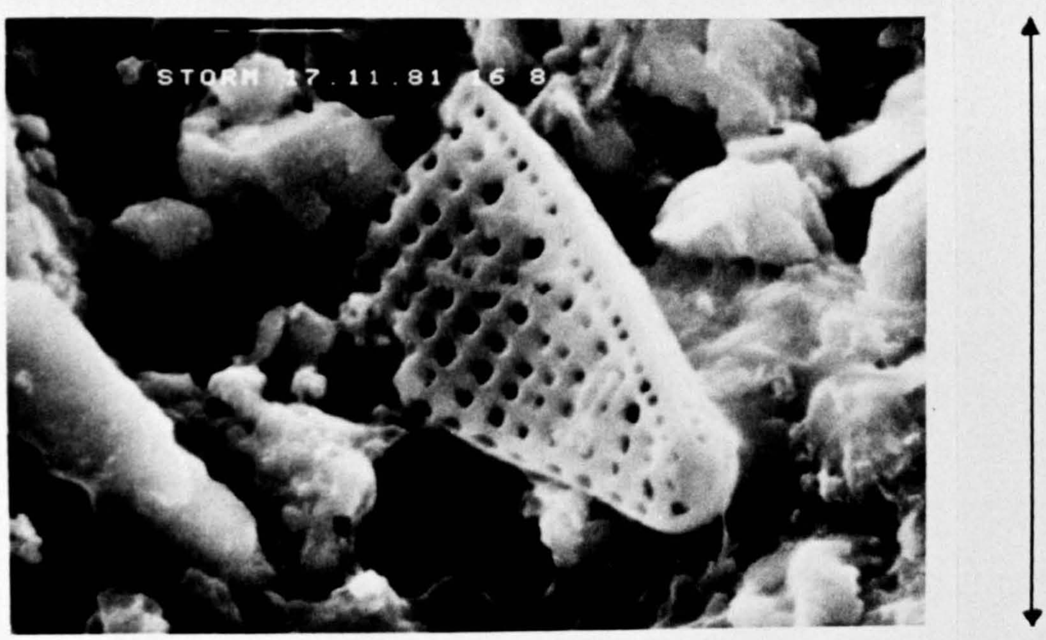


Elemental composition of diatom (Plate 1) from spot analysis on middle of test, showing dominance of silica.

PLATE 3 × 3200

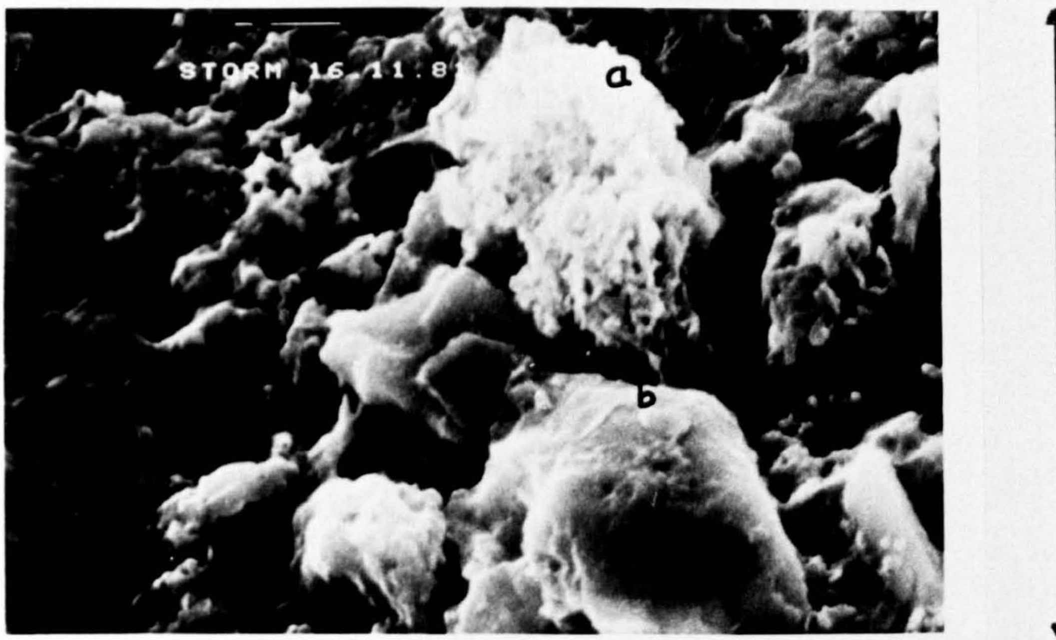
Congregated mass of diatom remains.

PLATE 4 × 2200



Broken piece of diatom test.

PLATE 5 x 9100



Silica-cemented aggregate showing upper particle supporting granular form of silica (a); lower particle is partially coated in early stages of orthogenic silica growth (b).

irregular granular appearance (Plate 3.5) which, judging by its brightness in the photomicrograph, is charging and therefore only loosely adhering to the substrate particle. It may in fact be a conglomeration of precipitates on very fine clay-sized individual particles. Secondly (Plate 3.5), there is a much smoother coating which may be optically continuous with the substrate particle having developed from it. Both types of coating are commonly seen with the precipitate intercementation of particles in aggregates.

3.3. Storm Classification.

3.3.1. The Basis of Storm Classification.

The hydrological characteristics of the storms monitored have been grouped to aid the interpretation of the data on particle size and surface texture. The classification was based on the rainfall intensity and total and on storm duration. The high proportion and rapidity of the runoff, which is typical of impermeable urban catchments (Hydraulics Research Station, 1980) results in the form of the hydrograph following very closely the pattern of rainfall. The data fell very largely into four groups despite each parameter being a continuum by nature, as described in Section 3.3.2. The values of the discharge parameters occurred in suites related to the dominant rainfall characteristics.

The manner in which the hydrological characteristics affect the sediment have been outlined in Section 3.2. The storm groups were characterised by the form of the particle size distributions (Chapter 5) and the nature of the surface texture (Chapter 8). As a result the effects of the hydrological characteristics can be used in the interpretation of the nature of the sediment.

3.3.2 The Analysis and Method of Classification of Storm Data.

The rainfall and discharge data for the 30 storms monitored were first examined as one data set and a multiple regression analysis made to determine the strength and nature of the relationships between the parameters. The equation of the line for the six parameters regressed on rainfall intensity is shown in Equation 3.1. The equation accounted for 70% of the deviation from the predicted values. A close relationship was to be expected as the parameters are derived from, and therefore dependent upon, one or more of the others.

Equation 3.1.

Y, intensity = 1.04 -(0.0692 x rainfall total)
-(0.0678 x storm duration) + (0.047 x discharge)
-(0.0351 x lag time) + (0.0888 x discharge duration)
-(0.167 x time to peak discharge)

To elucidate the interrelationships, Figure 3.1(i) to (vii) was constructed and the correlation coefficients calculated. The graphs of the most diagnostic parameters, rainfall intensity against storm length and rainfall total against storm length, show the data are clustered in four groups. The groupings are substantiated by plots of the remaining parameters. The four groups are detailed below in Section 3.4. Discharge is a poor discriminant between the groups since low and high values of rainfall total and intensity combine to give similar discharge values. In addition, the discharge is influenced by antecedent conditions. An already wet surface results in a higher proportion of runoff from subsequent rainfall, whereas a preceding dry period provides for evaporation, absorption and storage and thus reduced runoff.

Significance tests (Appendix 8) showed that for the majority of variables each storm group was significantly different from all others at the 95% level of significance. The overlap of some variables between two or more storms remains acceptable since it is the suites of variables which distinguish groups. Specific examples of distinct and diagnostic ranges of values describing each group are given in Sections 3.3.3 to 3.3.6.

3.3.3. Group I.

The storms in Group I are characterised by high initial rainfall intensity and short periods of duration. The values of the parameters for storms in this group are given in Table 3.2 and

TABLE 3.2.

STORM GROUPINGS OF HYDROLOGICAL PARAMETERS

Storm Date and Group	Mean Rainfall Intensity	Rainfall Total	Rainfall Duration	Discharge Peak	Lag	Discharge Duration	Time to Peak Discharge
	mm/hr	mm	hr	m^3/s	hr	hr	hr
Group I							
7.10.80	1.4	7.0	1.5	6.7	0.50	2.25	0.75
5.05.81	3.0	2.9	1.5	13.0	1.25	2.00	0.50
1.06.81	3.0	10.6	2.0				
11.09.81	1.6	5.8	2.5	(330)	4.00	2.25	1.00
14.09.81	1.0	12.9	2.5	11.0	1.0	2.50	0.75
18.09.81*	20.4	5.1	0.2	31.5	0.75	5.00	1.00
16.11.81	2.0	2.6	2.0	3.9	1.50	2.75	0.75
Group I and II							
17.11.81	1.8	8.9	4.5	10.0	1.25	3.75	0.75
Group II							
11.03.80	1.4	6.3	4.5	3.1	5.75	4.50	2.00
10.07.80	1.0	6.8	7.5				
6/7.10.80	2.0	12.9	7.0	8.5	7.00	8.00	2.00
10.10.80	1.0	9.1	8.5	5.9	6.25	8.25	3.65
11.10.80	1.0	5.5	6.0	7.7	0.00	6.00	2.50
3.05.81a	1.2	11.0	4.5	11.2	5.50	4.00	2.50
19.10.81*	2.4	19.1	8.0				
Group II and III							
19/20.11.81	1.4	5.3	4.0	8.4	1.00	9.0	2.75
Group III							
14.11.80	1.0	5.0	4.0				
30.03.81	1.2	6.9	1.5	6.4	9.00	4.50	1.75
3.05.81b	1.1	4.0	3.5	10.6	1.75	2.75	1.25
10.09.81	0.8	4.2	3.5	3.5	3.75	3.75	1.65
7.12.81	0.9	5.1	5.0				
Group IV							
5/6.3.80a	0.1	0.9	3.5	11.0	7.00	3.00	1.00
b	0.1	0.5	2.5	8.4	7.50	1.50	1.50
c	0.3	1.1	2.5	5.0	3.75	1.50	0.80
d	0.6	1.5	2.0	13.1	3.25	1.75	0.80
e	0.5	2.7	2.5	10.0	3.00	1.75	1.25
8.07.80	0.4	4.8	1.5	4.7	5.75	2.50	1.40
6.02.81	0.3	2.3	1.0				
17.03.81	0.5	1.4	3.0				
26.11.81	0.2	1.1	3.5				

* Extreme storms. (330) suspect data at high flows.

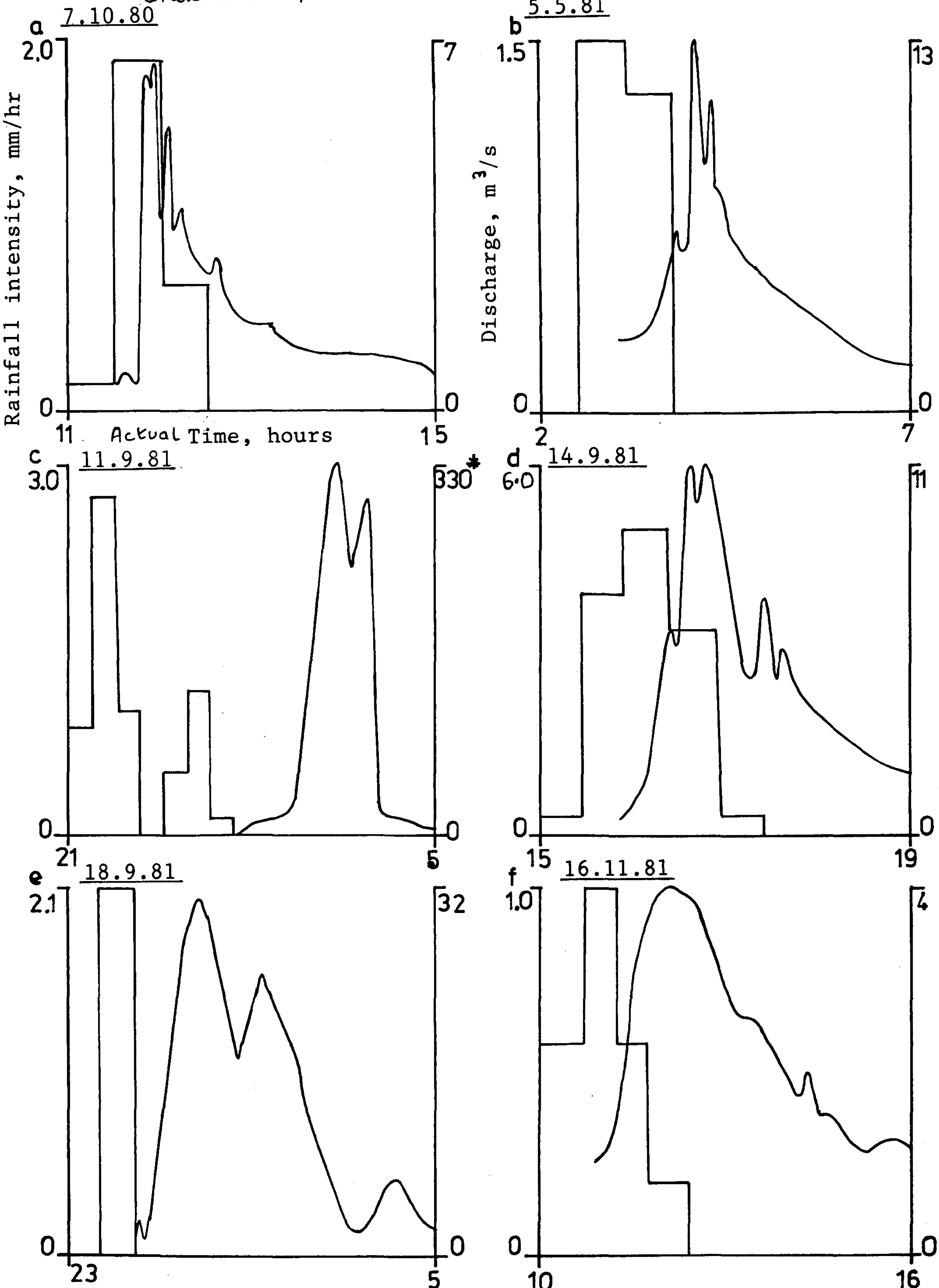
the rainfall intensities and hydrographs are shown in Figure 3.2. The four groups can be seen most clearly on Figure 3.1. (ii) of rainfall duration and rainfall intensity. The features of high initial rainfall intensity (Table 3.4) and short duration diagnostic of Group I are quite distinct from other groups. (Appendix 8). Rainfall duration occurs in the range 1.0 to 2.5 hr (Table 3.2) with intensities of up to 3.0mm/hr (Table 3.2), and in an extreme case up to 20.4mm/hr (Table 3.2), within the first hour. This is sufficient to generate high values of total rainfall of up to 13.0mm (Table 3.2). Most of the hydrological characteristics are positively correlated with each other, as can be seen from Figure 3.1. However, in the storms of Group I substantial discharge is generated in a short time by the high intensity rainfall. Lag periods are short and peak discharge is attained rapidly whereas rainfall duration and discharge duration are usually similar; discharge attained rapidly by high intensity rainfall takes up to 0.75 hours longer than the rainfall duration to regain base level. For example the storm of 7.10.80. Figure 3.2 with an initial rainfall intensity of 3.8mm/hour and mean intensity of 1.4mm/hour for 1.5 hours took 2.25 hours to return to base flow (Table 3.2).

Parameters other than rainfall intensity only influence the discharge when they reach high values. For example a relatively high rainfall total in the storms of 1. 6. 81 and 14. 9. 81 increases and prolongs the discharge towards the typical limits of this group (Figure 3.1.(i)). A slightly longer storm length creates a higher discharge and longer lag for the storm of 11. 9. 81 which borders on Group II characteristics. (Figure 3.1. (ii)).

The storm of the 18.9.81. (Figure 3.2.) is an extreme example of a Group I storm with an outstandingly high intensity of 20.4mm/hour over a period of just 15 minutes. The total rainfall was only moderate at 5.1mm but the discharge generated by the high intensity was 81.9 cumecs. (Table 3.2.).

FIGURE 3.2.a

RAINFALL AND DISCHARGE OF STORMS OF GROUP I:
drawn on expanded scales to show detail.

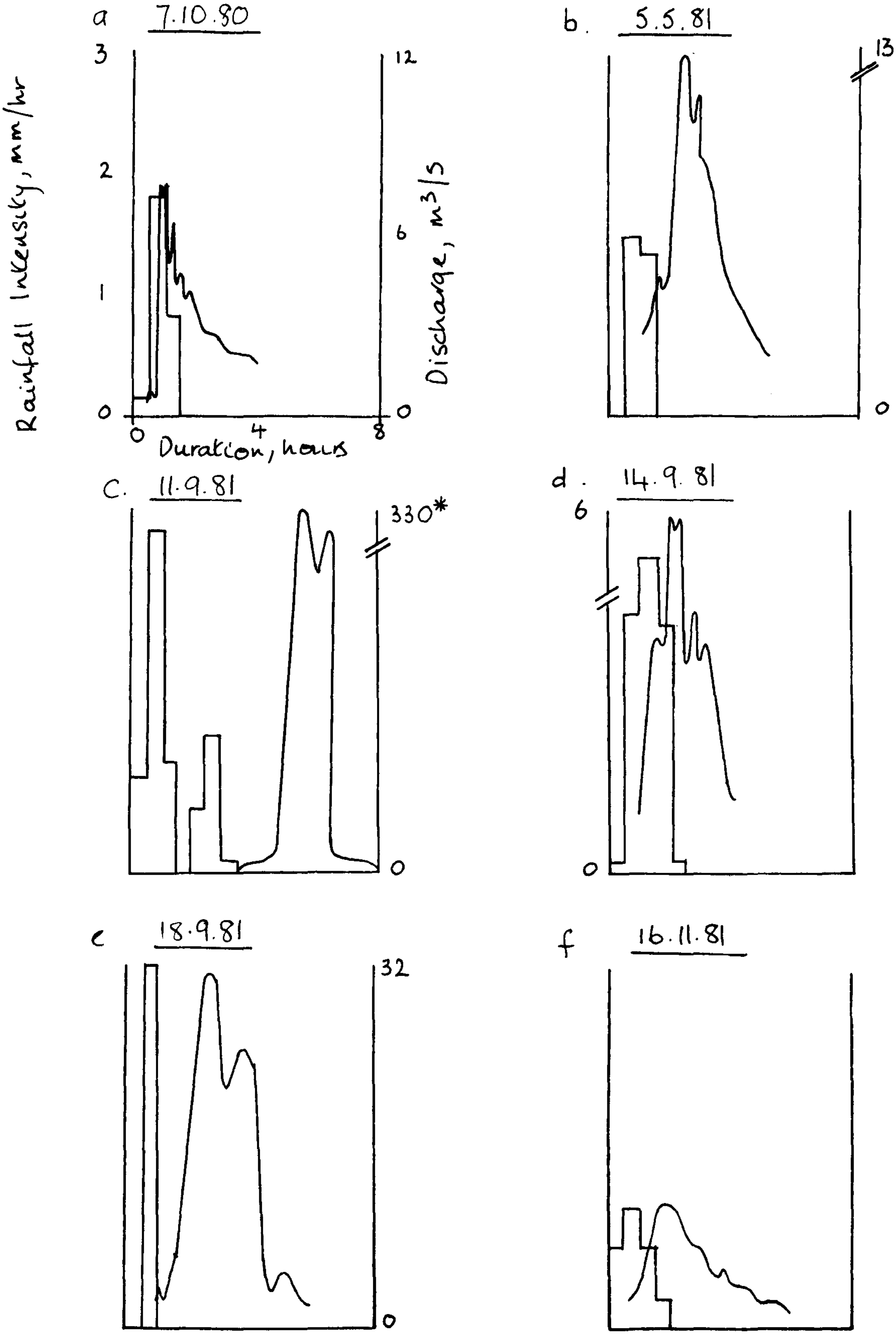


* High value, but suspect figure

FIGURE 3.2.b

RAINFALL AND DISCHARGE OF STORMS OF GROUP I

drawn on the same scale for ease of comparison.



Scale (unless otherwise stated)

Time	10mm : 2hours
Rainfall Intensity	30mm : 1mm/hour
Discharge	10mm : 2 m^3/s

The discharge duration was twenty times the rainfall duration compared with an average for the remaining storms of 1.2 times. This demonstrates very clearly the strong influence of rainfall intensity compared with rainfall total on the discharge and sediment control in this group. Despite the extreme nature of this storm it conforms to the characteristics of this storm group and thus exemplifies the form of the classification.

3.3.4. Group II

The storms classed as Group II are of the longest duration. Storms of up to 8.5 hours have been recorded with rainfall totals between 5.5mm and 12.9mm and continuous moderately high rainfall intensities as shown in Tables 3.2 and 3.3. The rainfall intensities and hydrographs are shown in Figure 3.3. The graph of the two most diagnostic features of Group II storms: rainfall total and duration, (Figure 3.1 (v) and Appendix 8 serves to distinguish storms of this group from others of the data set. All the rainfall and discharge parameters examined were positively correlated for storms in Group II with rainfall totals and discharge values predominantly at the higher end of the range as can be seen in Figure 3.1. The relationship between the time to peak discharge and rainfall intensity is the exception with a negative correlation as shown in Figure 3.1. (iv).

The storm of 19.10.81 was of exceptionally high total rainfall; 19.1mm of rain fell with moderate intensity over a period of 8 hours. Unfortunately, discharge data are not available for this storm because the force of the flow severed the sample intake pipe. However, the example further serves to demonstrate the validity of the classification.

3.3.5. Group III

Group III storms are classified by their mid-range values for all parameters as can be seen from the comparison of values in Table 3.3 The pattern of rainfall and discharge (Figure 3.4.)

TABLE 3.3. RANGES AND MODAL VALUES OF HYDROLOGICAL PARAMETERS FOR STORM GROUPS I-IV

Storm Group	Initial Rainfall Intensity mm/hr	Mean Rainfall Intensity mm/hr	Rainfall Total mm	Rainfall Duration hr	Discharge Peak cumecs	Lag Time hr	Discharge Duration hr	Time To Peak Discharge hr
Group I								
Range	2.8-5.0*	1.4-3.0	2.6-12.9	1.0-2.5	6.7-31.5	0.5-4.0	2.0-2.75	0.5-1.0
Modal Value	3.0		2,6,12	2.0		1.25	2.25	0.75
Group II								
Range	0.5-1.4	1.0-2.4	5.5-13.0	4.5-8.5	3.1-11.2	3.0-7.0	4.0-8.25	0.75-3.65
Modal Value	1.0		6.0	4.5,7.5	7.0	6.0	4.0,8.0	2.5
Group III								
Range	0.5-3.3	0.8-1.2	4.0-6.9	1.5-5.0	3.5-6.4	1.75-9.0	2.75-4.5	1.25-1,75
Modal Value	0.6		4.0,5.0	3.5		3.0	4.0	1.65
Group IV								
Range	0.2-0.7	0.2-0.7	1.1-4.8	1.0-3.5	4.7 -13.1	3.00-7.5	1.5-3.0	0.8-1.5
Modal Value	0.2	0.3	1.3	2.5				

* 20.4mm/hr, an exceptionally high value occurred on one occasion for a period of 15 minutes.

FIGURE 3.3.a

RAINFALL AND DISCHARGE OF STORMS OF GROUPS II: drawn on expanded scales to show detail.

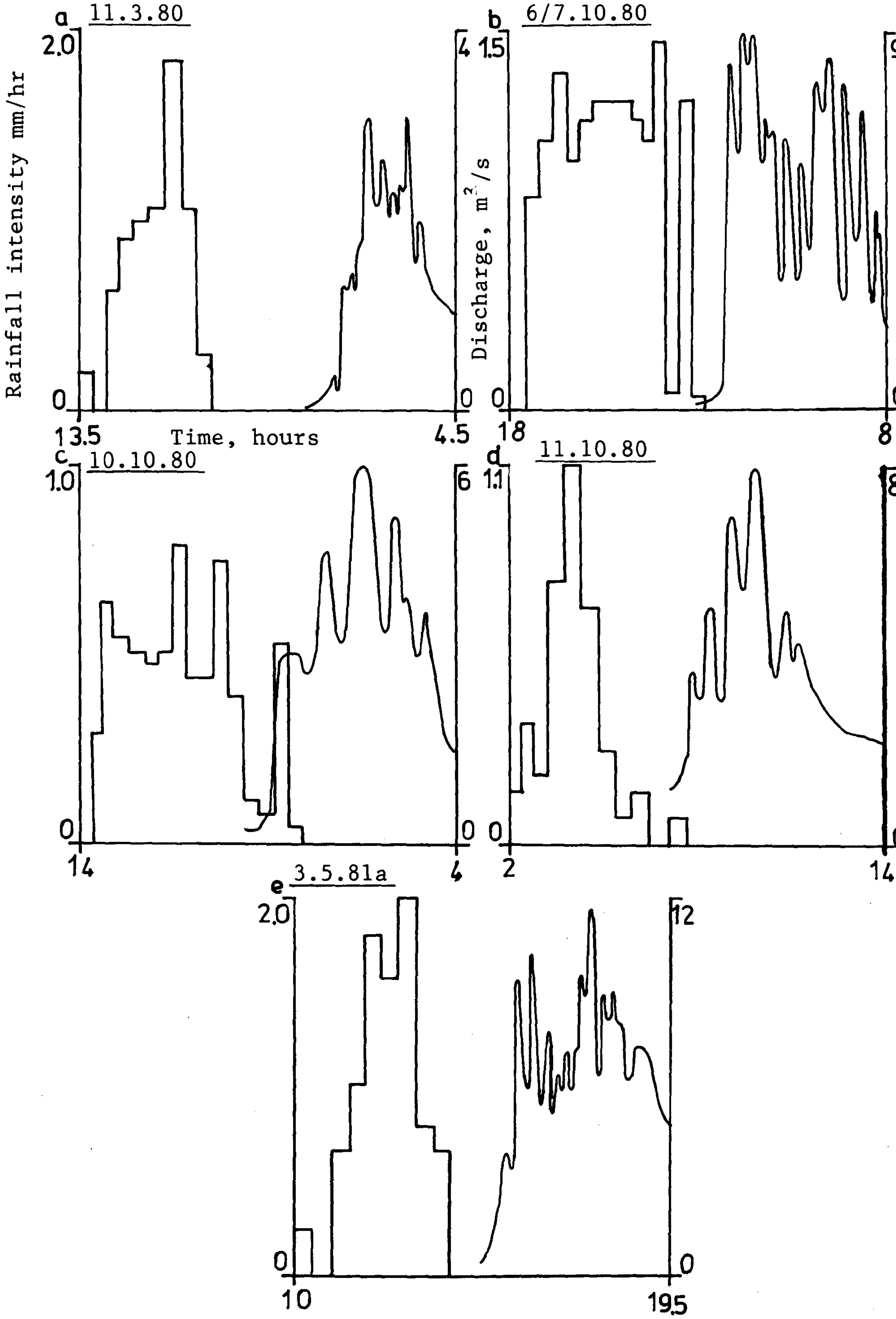
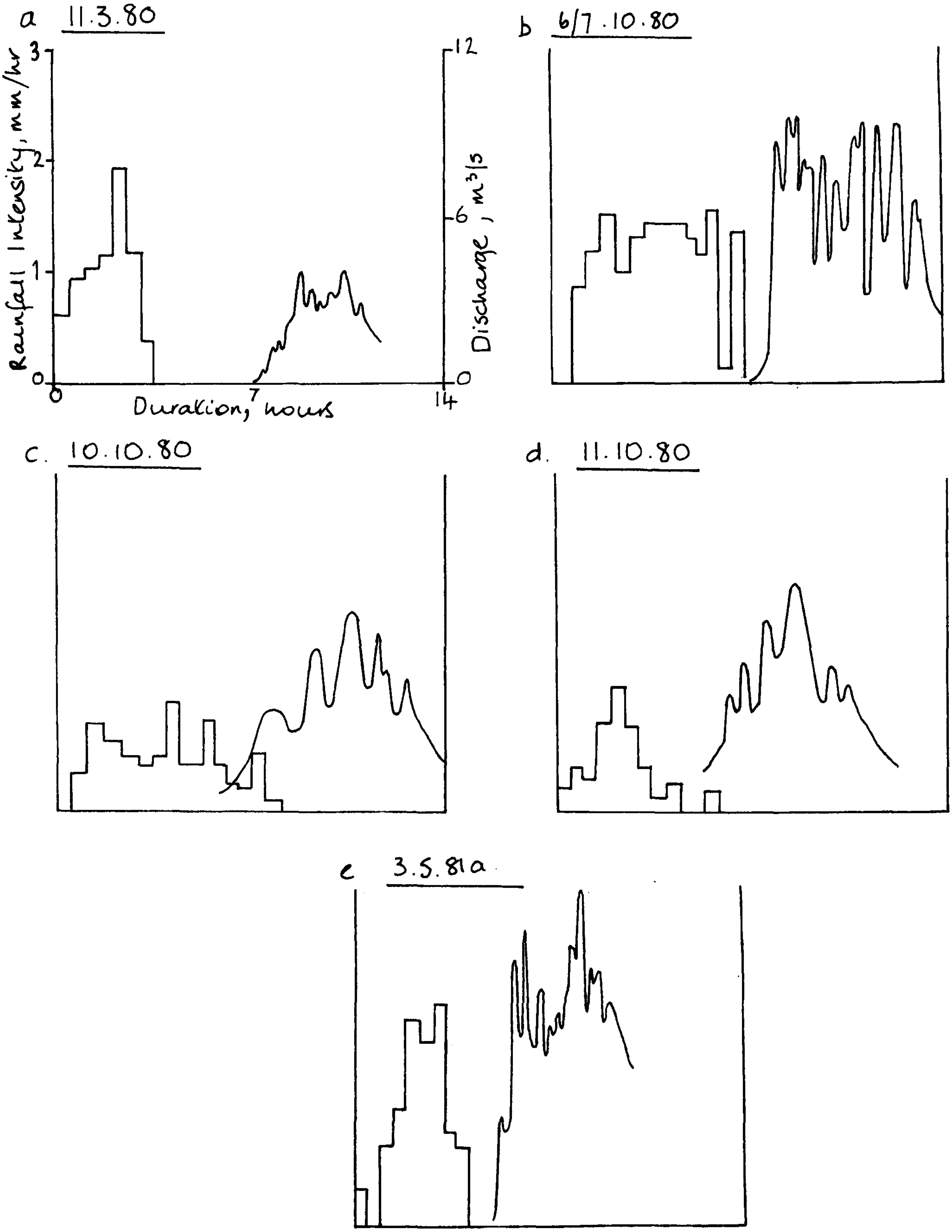


FIGURE 3.3.b

RAINFALL AND DISCHARGE OF STORMS OF GROUP II:

drawn on the same scale for ease of comparison.



Scale (unless otherwise stated)

Time 10mm : 2 hours

Rainfall Intensity 30mm : 1mm/hour

Discharge 10mm : 2 m^3/s

FIGURE 3.4.a

RAINFALL AND DISCHARGE OF STORMS OF GROUP III: drawn on expanded scales to show detail.

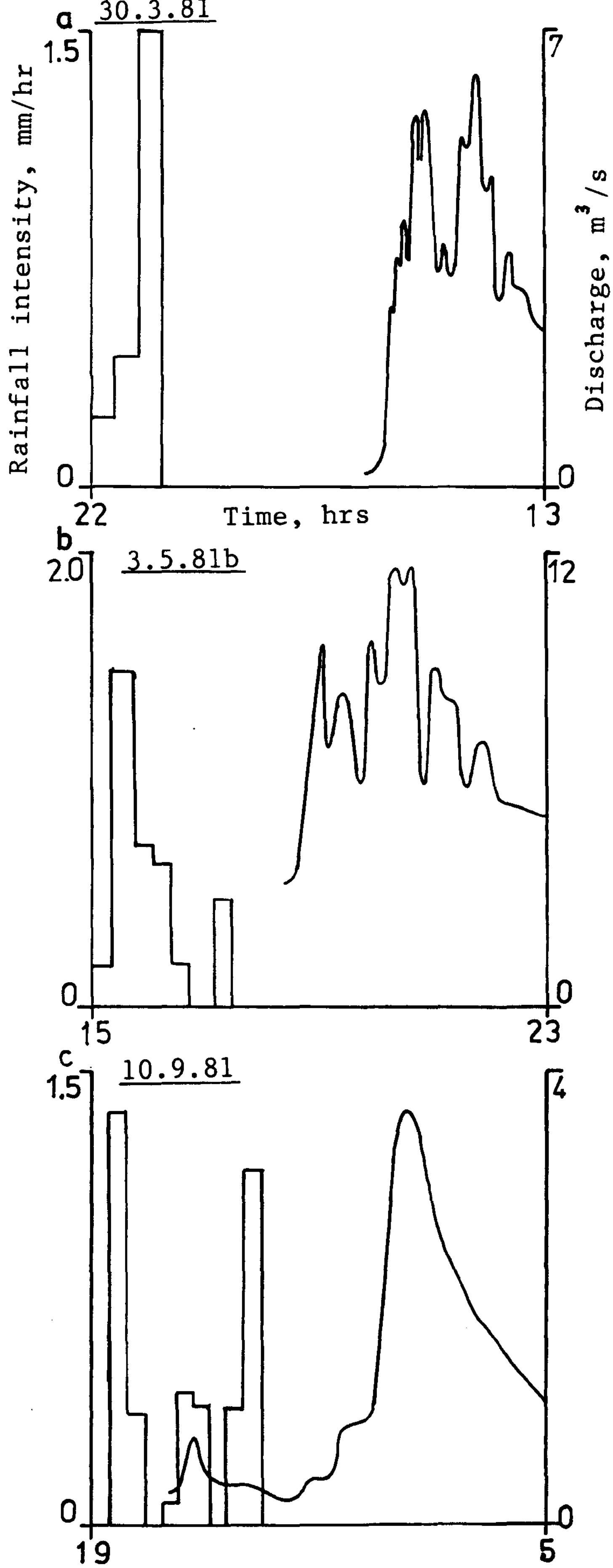
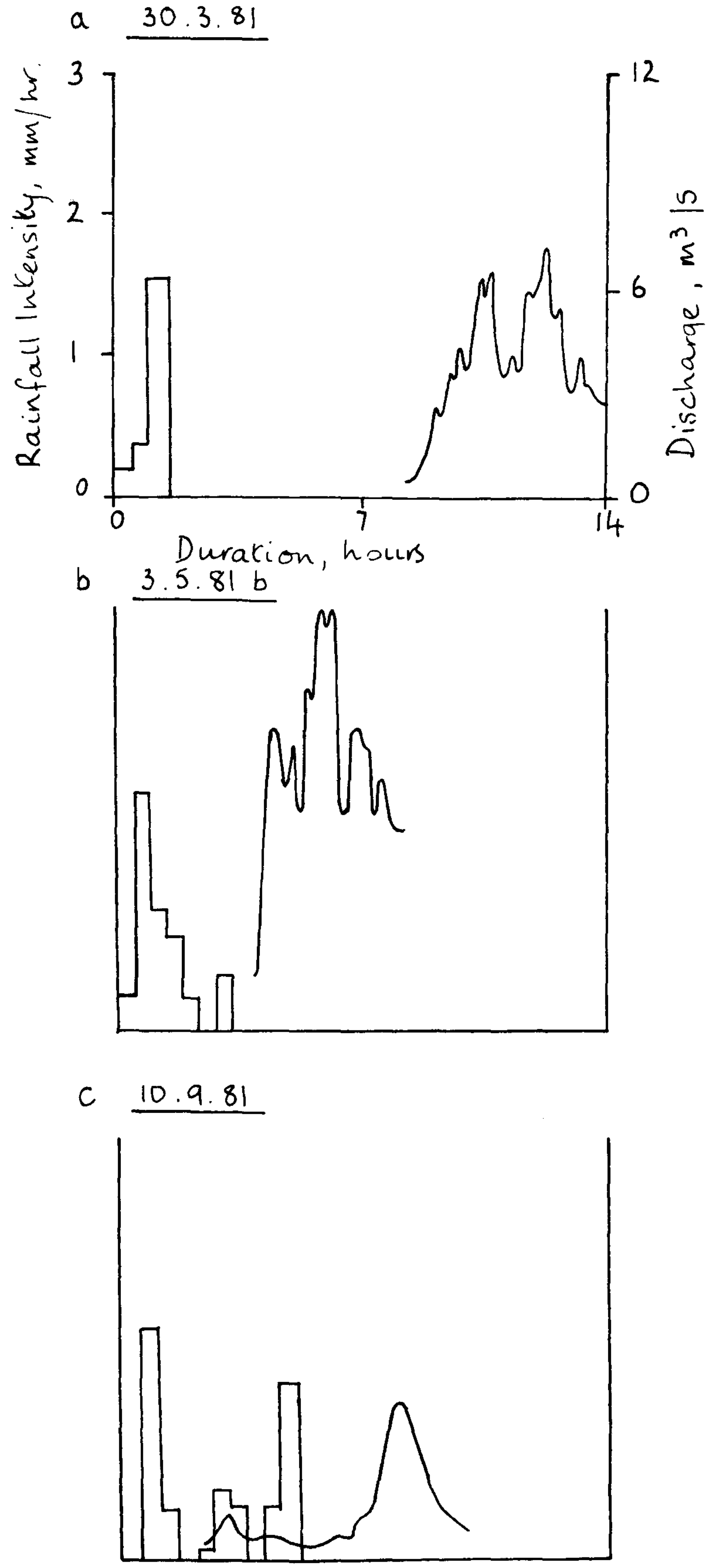


FIGURE 3.4.b.

RAINFALL AND DISCHARGE OF STORMS OF GROUP III

drawn on the same scale for ease of comparison.



Scale (unless otherwise stated)

Time	10 mm : 2 hours
Rainfall Intensity	30 mm : 1 mm/hour
Discharge	10 mm : 2 m^3/s

being governed largely by rainfall total and duration, is very similar to that of Group II. The parameters therefore have the similar relationships of positive correlations between rainfall total and intensity with the other parameters as in Group II storms, but with lower values. From Figure 3.1. it can be seen that Group III storms lie between those of Groups II and IV. Rainfall totals cover the range 4.0 to 6.9mm and storm durations are between 1.5 hours and 5 hours with 6 cumecs as the average discharge value (Table 3.3). Although the initial rainfall intensity of storms 3.5.81b and 10.9.81 is above the average for that group (Table 3.4), rainfall total and duration remain the overriding determinant parameters of the grouping.

3.3.6. Group IV

The storms in Group IV are among those of shortest duration with the lowest values for the rainfall (Appendix 8) and discharge parameters (Figure 3.5. The parameters are positively correlated (Figure 3.1 .) implying the dominant control by rainfall total and duration as for Groups II and III. Lag times tend to be prolonged in these events, for example 7.5 hours in the storm of 6.3.80b, probably because of the very low discharges requiring long periods to reach the outflow.

3.3.7. Storms of Mixed Grouping

Of the thirty storms studied three alone include features with diagnostic values from two groups. It is perhaps surprising that so few storms overlap the group boundaries since the values of the parameters are continuous. The recognition of these storms as a combination of two groups confirms the validity of the classification. The Groups I to IV have successive values for most parameters and as a result a storm of mixed grouping combines the properties of two adjacent groups. The two storms of 17.11.81 and 20.11.81 are of mixed groups due to the change in the nature of the rainfall during the storm, from one group to the

TABLE 3.4.

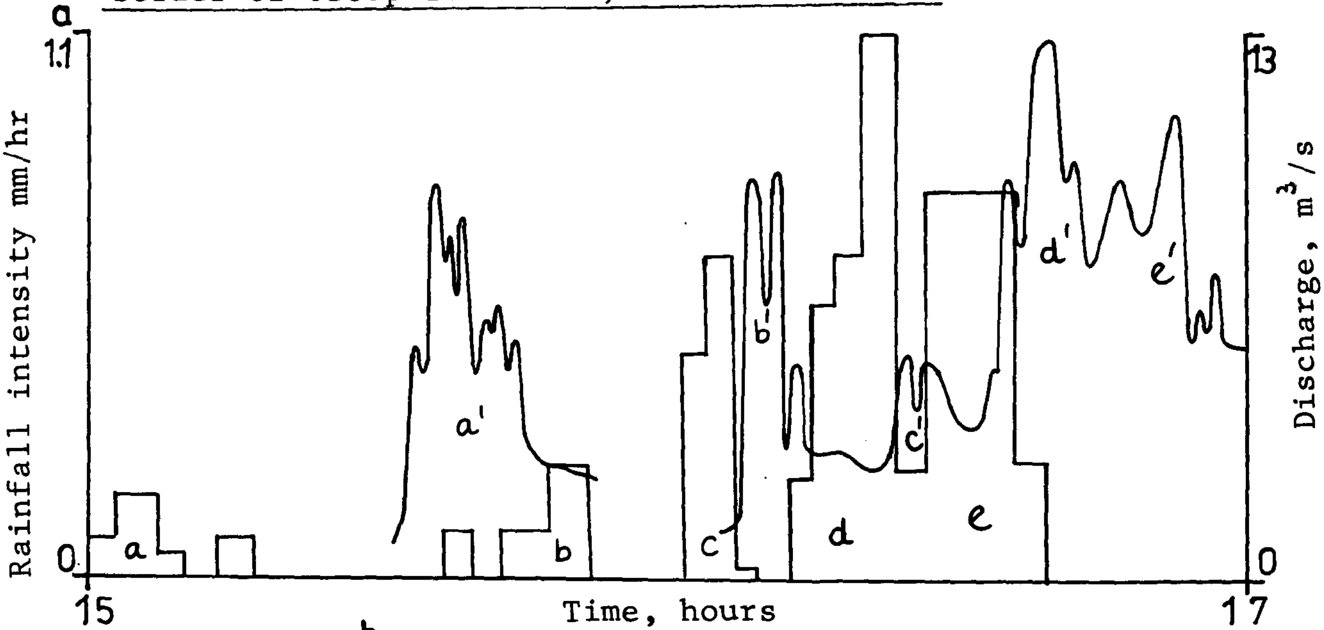
INITIAL RAINFALL INTENSITIES.

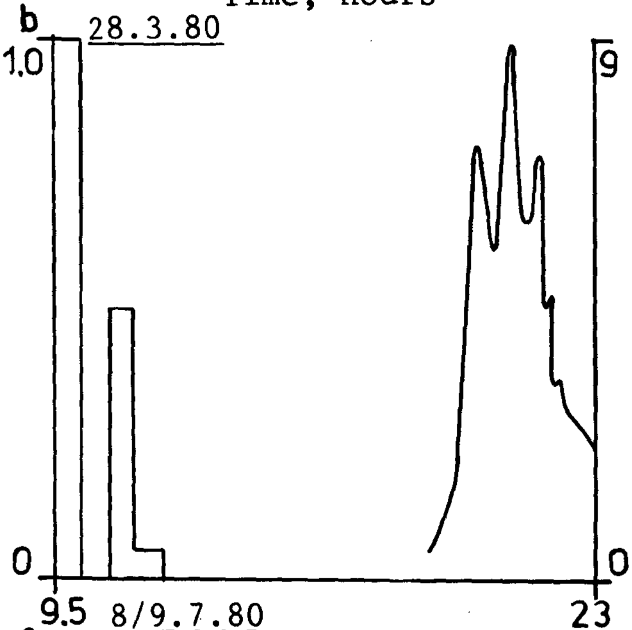
GROUP I		GROUP II		GROUP III		GROUP IV	
Storm	Initial Intensity mm/hr	Storm	Initial Intensity mm/hr	Storm	Initial Intensity mm/hr	Storm	Initial Intensity mm/hr
7.10.80	3.8			14.11.80	0.5	6.3.80 a	0.20
5.05.81	2.8	12.03.80	0.025	30.03.81	0.5	b	0.20
1.06.81	0.4	10.07.80	0.03	3.05.01b	3.3	c	0.70
11.09.81	5.0	6/7.10.80	1.40	10.09.81	2.8	e	0.74
14.09.81	2.8	10.10.80	0.80	7.12.81	0.8	8.07.80	0.10
18.09.81	20.4	11.10.80	0.50			6.02.81	0.02
16.11.81	2.1	3.05.81a	1.00			17.03.81	0.16
		19.10.81	0.07			26.11.81	0.015

FIGURE 3.5.a

RAINFALL AND DISCHARGE OF STORMS OF GROUP IV:
drawn on expanded scale to show detail.

Series of Group IV storms, 3.3.81 - 6.3.81





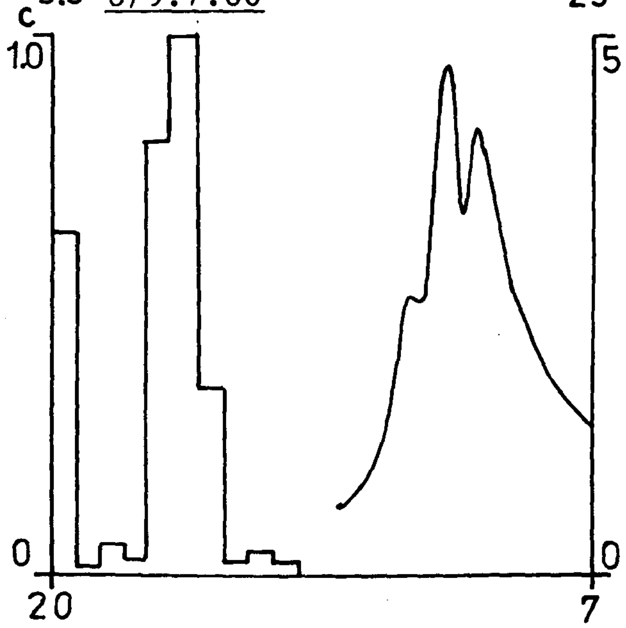


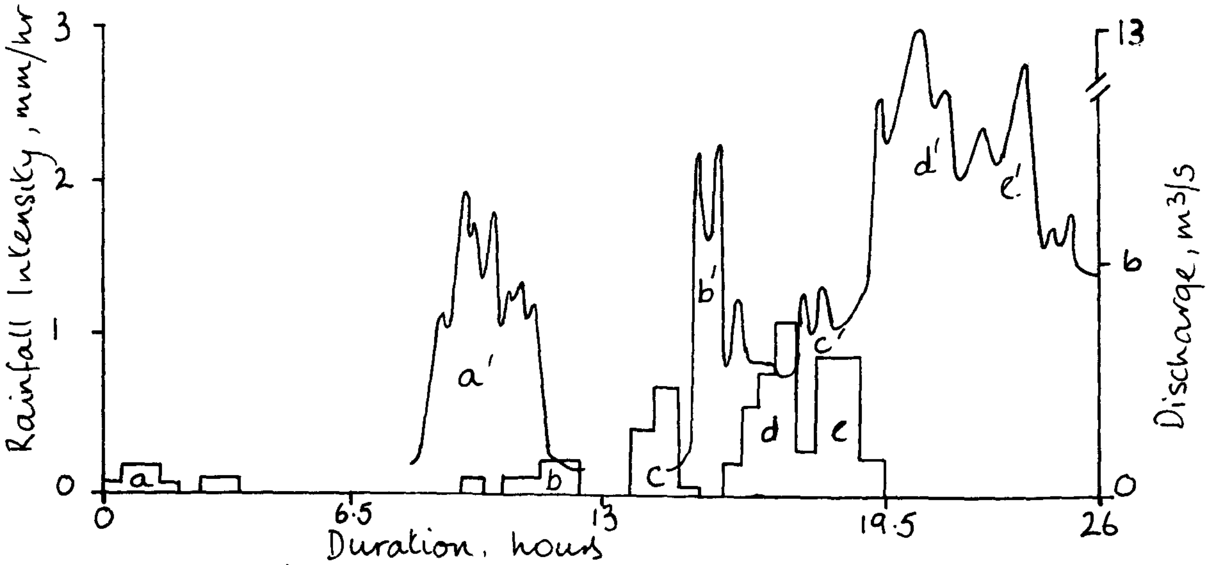
FIGURE 3.5.b

RAINFALL AND DISCHARGE OF STORMS OF GROUP IV.

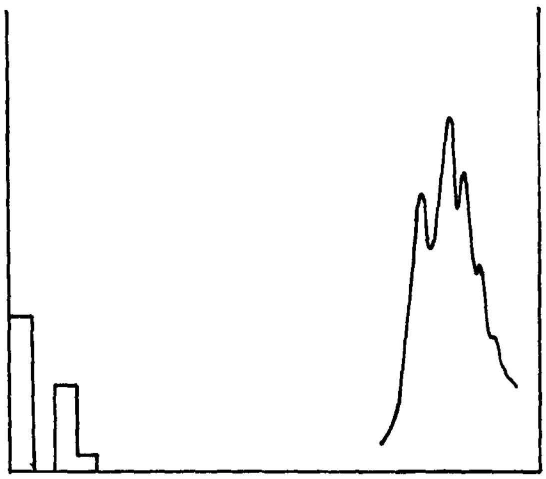
drawn on the same scale for ease of comparison.

a

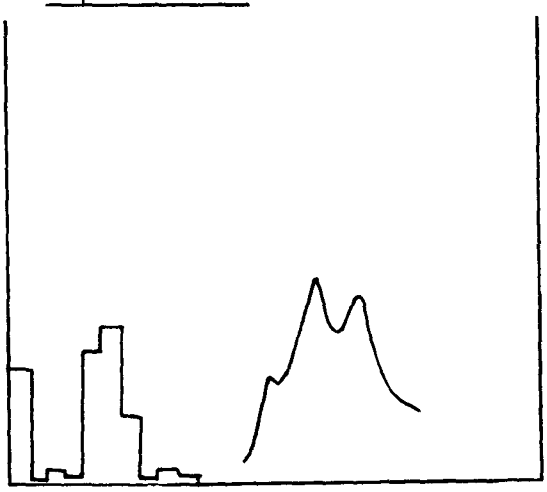
Series of Group IV Storms, 3.3.81-6.3.81



b 28.3.80



c 8/9.7.80



Scale (unless otherwise stated)

Time 10 mm: 2 hours

Rainfall Intensity 30 mm: 1 mm/hour

Discharge 10 mm: 2 m³/s

next. The storm of 17.11.81 (Figure 3.6) began as a Group I storm with an initially high intensity of 3.8mm/hr. In consequence there was a short lag time before the onset of storm discharge and a short time to peak. However, additional rainfall of only moderate intensity prolonged the storm to 4.5 hours which is beyond the range of Group I storms and into the lower range of Group II storms (Table 3.3). The hydrograph was substantially longer, by 1.5 hours, than the maximum for Group I storms and the discharge of 10 cumecs is common to both groups.

The storm on 20.11.81 (Figure 3.6) was classified as a mixture between Groups II and III. The storm was of 4 hours, a moderate duration (Tables 3.2 and 3.3), but a peak rainfall intensity of 4mm/hr in the second hour increased the intensity, total and discharge to values in the ranges of Group II. The peak rainfall also unusually prolonged the discharge duration considerably in excess of the storm length to values in the range of Group II.

The storm of 11.9.81 (Figure 3.2) was of very high initial intensity and was classified in Group I but the inclusion in the hydrograph of discharge from rainfall in the preceding 1.5 hours, after a break of 1.5 hours, increased the discharge length closer to the values of Group II than I. The rainfall total was representative of both groups. Group I classification was thus maintained to accommodate the diagnostic initial high intensity and because the majority of remaining features comformed to Group I value.

At first these storms, with their values of parameters included in the ranges of different groups, appear to fall between two groups of the classification. However, closer inspection reveals that such rainfall events comprise two different types of storms occurring in swift succession. The classification is able to distinguish between the two and their respective effects on the discharge.

FIGURE 3.6, a

RAINFALL AND DISCHARGE OF STORMS OF MIXED GROUPING: drawn on expanded scale to show detail.

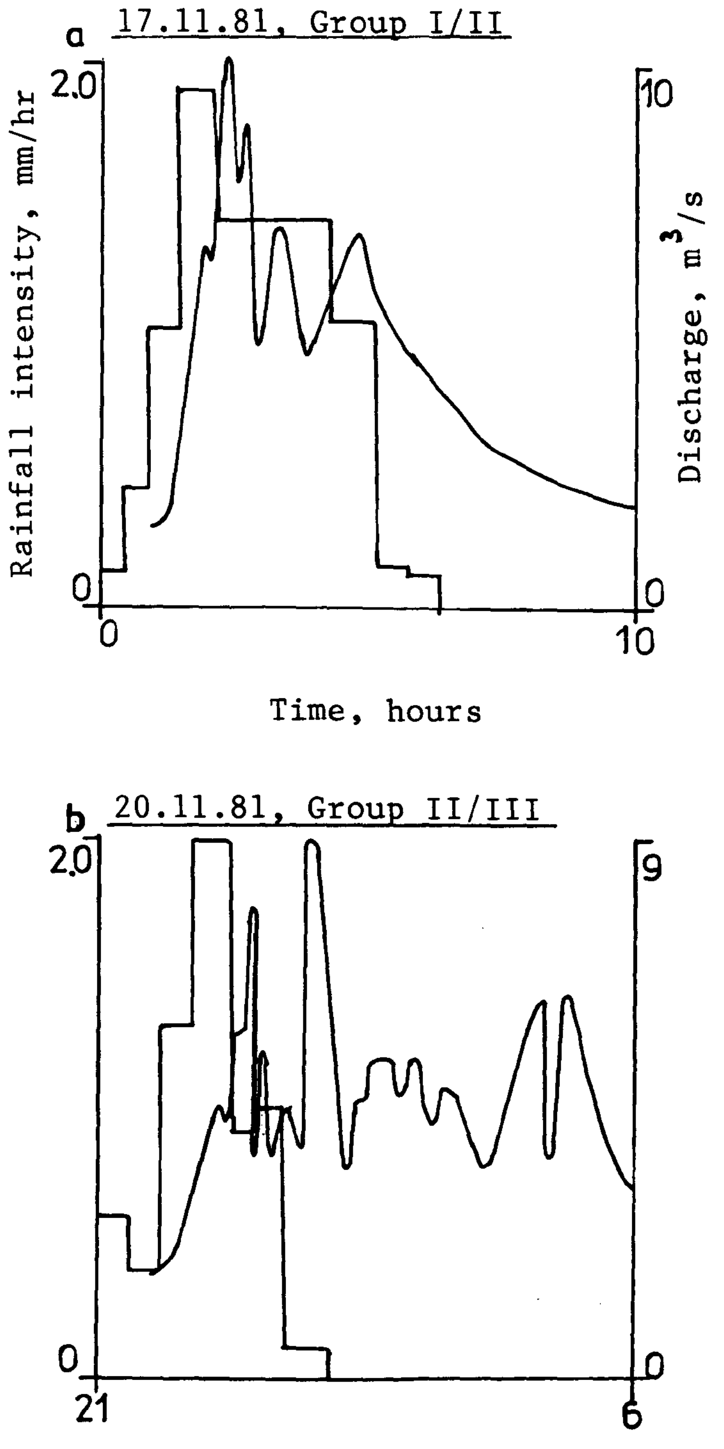
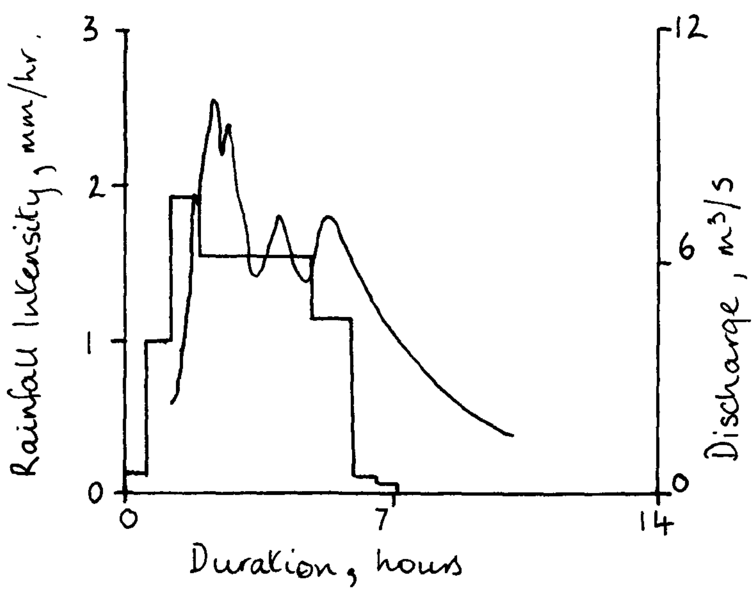


FIGURE 3.6.b

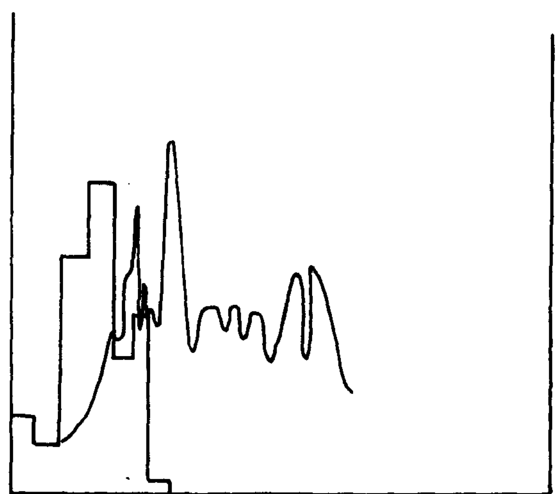
<u>RAINFALL AND DISCHARGE OF STORMS OF MIXED GROUPING:</u>

drawn on the same scale for ease of comparison.

a <u>17.11.81 Group I/II</u>



b <u>20.11.81 Group II/III</u>



<u>Scale</u> (unless otherwise stated)

Time	10 mm:	2 hours
Rainfall Intensity	30 mm:	1 mm/hour
Discharge	10 mm:	2 m^3/s

PART II

PARTICLE SIZE ANALYSIS

CHAPTER 4

THE MEASUREMENT OF SEDIMENTS BY ELECTRONIC SENSING ZONE ANALYSER.

4.1. Introduction

Electronic particle counters were originally designed in the early 1950's for the rapid measurement of large numbers of red blood cells (Coulter, 1956). Some of the early work, for example by Brecher, Schneider and Williams (1956), described the use of the electronic counter in the reliable estimation of mean corpuscular volume. Subsequently, as the technique was developed, uses were found for it in a diverse range of fields which include particle size measurements for: industries using powders in paints (Crowl, 1966), ceramics (Lines+Wood,1965;Lines 1973), pharmaceuticals (Anderson, 1965), the analysis of airborne particles and in particular those which cause health hazards from chimney emissions such as asbestos (Hidy, 1975; Paciga and Jarvis, 1976; Lodge, 198I), dust produced in textile mills (Matlock, Wiederhold and Parnell, 1975), explosives (Schullion, Harris and McCormack, 1970), and for forensic science (Dudley, 1977).

The electronic analyser has been used in the measurement of a variety of fluviatile and detrital sediments of which a few examples are mentioned here to demonstrate the considerable advantages of the technique over previously used methods. The work done on fine sediment, predominantly less than 500μm, has largely been either to analyse sediments of low concentration or to compare the greater speed and efficiency of the electronic counter with more traditional sedimentation and sieving techniques. The outstanding advantage of the electronic counter over other techniques is the ability to measure very fine sediments, less than 1μm, rapidly and from a small sample. Sheldon and Parsons (1968) examined a variety of marine sediments with the Coulter Counter in the size range of 3 to 100μm. This single technique.

allowed the measurement of a wide range of particle sizes with the advantages of requiring only one method of sample preparation and the production of one set of results over the entire size range. In contrast, it can be seen that when a variety of sedimentation and sieving techniques are used to cover the size range of a single sediment, allowances must be made for different parameters being measured by different techniques, for example settling velocity or a predetermined particle diameter. The rapidity of the method is demonstrated by McCave and Jarvis (1973) who were able to analyse fine and coarse sand (160µm, 400µm) at a concentration of 0.1 to 0.5 g/L on a preset time of sixty seconds per sample. The dilute concentration of sediment required by the Coulter Counter recommended it to Walker, Woodyer and Hutka (1974) for their measurement of low concentrations of suspended sediment in streams. This was particularly crucial in their investigation into the large discrepancy between the low sediment concentrations in Eastern Australian streams compared with the levels they had found in North America. In the studies of the changes in particle sizes of stormwater sediment (Ellis, Hamilton and Roberts, 1981) the detailed results from the Coulter Counter and the high degree of reproducibility gave reliable results for variations between successive samples. Inferences could then be made on the hydraulics of the transport of fine sediment, and later these results could be related by hydrological parameters (Ellis, Hamilton and Roberts, 1982).

The principle of the technique is widely described in the literature, for example by Coulter (1956), Ullrich (1960), Allen (1966), Sheldon and Parsons (1967), Walker and Hutka (1971), Swift, Schubel and Sheldon (1972) and Griever (1976). The instrument is set up with one electrode inside the orifice tube and a second one on the other side of the aperture. The whole is immersed in electrolyte thus allowing an electrical field to exist between the electrodes. The particles are drawn through the aperture under vacuum and as they pass through, the resistance across the aperture alters. The change in resistance is proportional to the volume of the particle which is determined as the spherical-equivalent of the diameter that passed through the aperture. The change in the resistance produces a pulse which is recorded in the appropriate size channel.

The purpose of the stormwater sediment particle size measurement was to establish the sediment sizes in runoff across the catchment and along the drain during different types of storms.

4.2. Sample Preparation for Particle Size Measurement by an Electronic Sensing Zone Analyser.

4.2.1. Subsampling.

As very small samples of approximately 5g are required for analysis by the Coulter Counter it is important to ensure that they are representative of their sediment source (Walker, Woodyer and Hutka, 1974). For this reason, the method of obtaining small subsamples from the larger samples collected in the field, such as the stormwater samples, has been critically examined. Lloyd, Stenhouse and Buxton (circa 1975) reviewed three techniques to compare the sampling error with the irreducible error. One subsample was drawn by pipette from a well-shaken larger sample; a second subsample was poured from the main sample container which had been shaken vigorously immediately before pouring; and a third method used a Burt Sampler in which a concentrated sample is subdivided into six by forcing a well-stirred concentrated suspension with compressed air through six capillary tubes. The subsamples were dispersed and diluted to suit the Coulter Counter. The pipette method showed too great a variation between samples but the other two methods were comparable. In addition to these considerations the stormwater sample preparation method was aimed at producing the optimum results with the minimum of alteration to the natural form of the sediment.

On collection all the stormwater samples were treated with sodium azide of 0.5% concentration to destroy the algae present and thus prevent its growth from causing flocculation of the particles. Alternatively some authors, for example Shideler (1976), oxidised the organic matter in the samples as the volume of organic matter would distort size analysis results. The method of stormwater sampling, described in Chapter 2, provides samples of 500ml throughout the stormflow. For the particle size analysis with the electronic counter subsamples of 5 to 10ml were required, depending upon the sediment concentration. Too great a quantity of sediment would need considerable dilution for the analysis. To be as representative as possible the subsamples had to be randomly selected and had to contain the full range of particle sizes in the same proportions as the parent population. The method of thoroughly shaking the sample and then immediately pouring off 5 to 10ml has been shown to be the simplest and one of the most effective methods of sub-sample selection (Lloyd, Stenhouse and Buxton, 1975). Using this method for the stormwater analysis, the samples can be taken in their native medium directly from the original sample containers without delay and without affecting the sediment in anyway. Further, the method is rapid which is a considerable advantage when dealing with twenty-four or forty-eight samples from each storm.

4.2.2. Methods of Dispersion.

The method of particle dispersion in samples prepared for electronic particle measurement has been found to be of paramount importance in producing accurate particle size distributions. Chemical and mechanical dispersants are used which separate those particles loosely joined by cohesive forces and distribute them as randomly as possible throughout the solution. Mechanical agitation with an ultrasonic bath or probe are commonly used before the analysis and stirring is often continued during the analysis to minimise the settling out of larger particles. The use of a round-bottomed sample beaker is recommended by the Coulter Counter Manual (Coulter Electronics, 1978) for the maximum efficiency of stirring. Several authors, for example Nieriow and Ang (1972), have argued about the positioning of the stirrer, particularly to prevent eddies from forming close to the aperture. Walker and Hutka (1971) stirred samples to maintain the particle concentration during sampling but some zones were protected from this by the aperture tube and the electrode; as a result flow patterns were set up. Phelps and Maguire (1957) found that, of the chemical dispersants, sodium polyphosphate salts were the most thorough dispersant and required a minimum of agitation. More sophisticated methods have been derived from this; Walker and Hutka (1971), in their work on soils, used sodium hydroxide and sodium tripolyphosphate as the dispersant. However the latter could not be widely adopted because it had no significant effect on reducing flocculation. After preliminary trials with Nonidet - 42, Lloyd, Stenhouse and Buxton (circa 1975) found they were not producing a Poisson distribution of the counts as would be expected from fully dispersed, randomly distributed particles. This was caused by the reagglomeration of the particles after the initial dispersion and was confirmed by the standard deviation of the counts between channels which indicated a non-random distribution. The authors found sodium pyrophosphate was a successful replacement. Walker, Woodyer and Hutka (1974) started their sample dispersion with samples too coarse for the Coulter Counter. The entire sample was disaggregated with an ultrasonic probe without breaking down the grains. Settling out in water then induced a size separation and the suspended material was treated with sodium chloride as the dispersant. Guy (1967) examined the preparation of sediment samples removed from their native water. For this he advocated the use of sodium hexametaphosphate and sodium carbonate in distilled water which were mixed mechanically with the particles for five minutes. ASTM (1971) and Shideler (1976) also favour sodium hexametaphosphate for routine sediment analysis.

As the stormwater particles in their natural state occur as cemented aggregates with individual loosely adhering particles there was the problem of achieving the correct degree of dispersion without destroying the aggregates. Various methods were attempted and the results of each were examined under the microscope although caution was required to ensure filtering prior to microscope mounting did not itself cause flocculation. Initially sodium hexametaphosphate was used to disperse the particles and was introduced directly into the stormwater samples. Subsequently however sodium pyrophosphate was found to be a more thorough dispersant of the stormwater samples and 40ml, at a concentration of 0.1%, was added to each subsample. Aggregates were found to resist agitation in the ultrasonic bath (Chapter 9) and stirring was thus safely used to help to maintain the dispersion of the particles throughout sampling; stirring was at a slow rate to avoid generating air bubbles which cause anomolous readings.

4.2.3. The Choice of Electrolyte.

Electrolytes must, firstly, have as low an aperture resistance as possible. High resistance produces background noise and reduces the instrument sensitivity. Further, excess resistance at the aperture may cause heating and the release of fine air bubbles which become attached to the internal electrode and reduce its effectiveness (Walker and Hutka, 1971). Secondly, the electrolyte must not cause flocculation of the fine particles which would result in artificially large particles being measured and may cause settling in extreme cases. Often this can be prevented by constant stirring. The most popular choice of electrolyte is sodium chloride although it depends on the sediment involved. ASTM (1971), Lines and Wood (1965), Wood and Lines (1966) and Lloyd, Stenhouse and Buxton (circa 1975) used sodium chloride successfully although Lloyd et al recommended filtering under pressure if necessary, to increase the amount of dissolved air sufficiently to maintain a random distribution. Sodium hexametaphosphate was used in routine mud analysis by Shideler (1976) which was a compromise to provide a minimum of flocculation and a low background count and to avoid obscuring fine particles. McCave and Jarvis (1973) used a saline glycerol in which the high viscosity maintained fine particles in suspension. The advantages of this have to be weighed against the disadvantage of blocking the finer apertures. A further reason for the use of a non-aqueous based electrolyte is in instances when particles are water-soluble. Giever (1976) has shown that the dissolving of particles can be detected by a drop in the count rate and remedied by a change to an alcohol-based electrolyte.

For the stormwater sediment a commercially produced electrolyte of sodium chloride, "Isoton", was added to the sample and dispersant. This electrolyte fulfilled the requirements for successful sampling and did not need to be filtered. Between 25ml and 50ml sodium chloride were added to the sample and dispersant until the solution was diluted to a concentration of 15% which was recommended by the manual (Coulter Electronics, 1978) and indicated on the concentration gauge. The preparation was stirred to ensure proper mixing before the concentration was measured.

4.3. The Mode of Operation of the Electronic Counter.

4.3.1. Instrument Settings.

The Electronic Coulter Counter, Model TAII, was set up according to the manual (Coulter Electronics, 1978). The instrument had to be located well away from any source of microphonic vibrations, electronic noise or electromagnetic radiation which would produce undue electrical interference (Shideler, 1976). The manometer was operated by hand and the instrument was reset automatically. The length of time taken for data accumulation depended upon the aperture size, as described below. All sixteen channels were monitored and the results plotted and printed for differential and cumulative volume and differential and cumulative number. The total counts for each sample and the time taken for each analysis were also recorded.

4.3.2. Aperture Size and Time Periods of Analysis.

The aperture size should be chosen so that between approximately 2% and 40% of that size covers the sample particle size range. Particles of diameter of 1 to 2% of the aperture size tend to be swamped by electronic noise and particles of more than 40% tend to block the aperture (Harris and Jowett, 1965; McCave and Jarvis 1973). In this study the upper size percentage is frequently between 40 and 50% of the aperture size which was usually 100μm and gave a particle size range of approximately 1 to 40μm. The time taken for each analysis was consistently within 0.2 seconds of the mean time taken. For example, 20 samples from one storm, analysed with the 100μm aperture, took predominantly 52.0 seconds within the range of 51.9 to 52.3 seconds. Any longer period indicated some mal-function of the instrument, usually a blocking of the aperture, which had not been noticed on the pulse-height recorder when the count build-up was being observed. A blockage can be instantly recognised on the pulse-height recorder by the appearance of a single horizontal line. The aperture of diameter 140μm normally covered the range of sediment collected from a high-intensity storm with 24.5 seconds taken for each analysis. Occasionally the 50μm diameter aperture was used in conjuction with the 100μm aperture to cover the extended fine range of the size distribution of the sediment sampled either from storms during exceptionally low flows, or from those immediately following a more severe storm which had flushed out the coarser sediment. The smaller aperture required approximately 169 seconds for each analysis. Very exceptionally the 200μm aperture was required to cover the greater range of sediment of hand sampling (12.6 seconds). However, if the majority of the sediment was well below the maximum size a representative size analysis would not be obtained using the large aperture. As a smaller aperture would become blocked by the larger particles it is more satisfactory to sieve the sample to remove the coarse fraction (Swift, Schubel and Sheldon, 1972).

Brief mention must be made of the resistivity of the particles. Variation in resistivity between particles is not important (Sheldon and Parsons, 1968) providing they are of greater resistivity than that of the electrolyte. This is no problem for geological sediments (Swift, Schubel and Sheldon, 1972). Working on powders, Wood and Lines (1966) found that particle resistivity had no significant effect on instrument response partly because the powder in suspension behaves as a non-conductor due to oxide films forming on the particle surface. Wood and Lines (1966) showed that density does not effect the results although temperature may effect the resistivity of the electrolyte but this can be countered mathematically.

4.3.3. Calibration of the Instrument.

According to Sheldon and Parsons (1967) the aim of the calibration is to define the relationship between the particle volume and the electrical pulse strength for each aperture as:

$$\Delta R = K\left[1 - \frac{\rho_E}{\rho}\right]$$

where ΔR is the change in resistivity caused by the particle, K is the aperture constant and $\frac{\rho_E}{\rho}$ is the electrolyte resistivity, and the electrolyte resistivity is negligible; the change in resistance depends on the particle resistivity. From such reasoning Lines and Wood (1966) have shown

$$d = K \times \sqrt[3]{\text{instrument settings}},$$

where d is the particle diameter.

The instrument is calibrated using monosized particles such as pollen grains or, as in the present study, commercially produced latex. The size of the calibration particles selected should be approximately the middle of the size range which is 10 to 20% of the aperture size. Using one particle size for one aperture size the remaining particle sizes in that range can be calculated. Calibrations can be extrapolated to other apertures but the calibration operation is quick and straightforward and it is more reliable to calibrate each aperture separately. The split-peak method described in the manual (Coulter Electronics, 1978) was adopted with the latex, for example 8 to 45μm for the 100μm aperture, which fell in channels 8 and 9. The aperture-matching switch was adjusted until the two peaks were of equal frequency. The error was calculated by McCave and Jarvis (1973) as $\pm$ 1.6% at the 95% level of significance. A logarithmic scale of particle volume was used for the stormwater sediments which spanned two, and sometimes three, orders of magnitude.

4.4. The Accuracy of the Measurement Procedure.

4.4.1. Over-reading and Coincidence.

The main criticism of the technique is that as a result of taking the spherical-equivalent of the particle diameter the instrument appears to over-read compared with other techniques described in 4.5. Although this is the most widely described error, Sheldon and Parsons (1968) point out that in a sample of elongate sediment the results may be under-read whereas in a mixture of sediment the problem may be minimal. From observations of the stormwater sediments this appears to be most reasonable as in the case of elongate particles sucked through the aperture in the most streamlined manner. An additional source of error is described as the 'Coincidence Theory' and refers to the problem of two or more particles entering the aperture together. The particles are measured either as one larger particle or the smaller one is masked by the largest particle. However different authors have provided different approaches to the problem.

Wales and Wilson (1961) considered that coincidence errors occur frequently and adopted the various correct methods, set out in the particular instrument manual, to reduce consequent size over-reading. They, as well as Walker and Hutka (1971), described the problem graphically and demonstrated clearly the various types of coincidence error. Two particles in the aperture together produce one pulse representing (a) the sum of the combined particles, (b) the size of the largest particle, or (c) an intermediate combination between (b) and (c).

Princen and Kwolek (1965) agreed with the classes of coincidence occurrence described above but favoured the sum of the combined particles as the more frequent event whereas Wales and Wilson (1961) thought the result was predominantly the size of the largest particle. Princen and Kwolek (1965) described coincidence from combined particle dimensions as 'vertical' action and hypothesised that if both a large and a small particle are in the orifice together the larger particle would register a pulse. 'Horizontal' action was described as the passage of two particles through the sensing zone in the manner of one larger single particle and were measured as such. These hypotheses are based on the assumption that the particles being sampled are randomly distributed in the electrolyte. If that is so there should be little likelihood of two particles occuring together at all but in that event they would be counted as one.

So far all the theories have been based on the assumption that the particles are randomly distributed with a Poisson distribution but Seymour (1969) decried all the coincidence theories based on this assumption. He maintained that particles occurred in groups and demonstrated this from the analysis of particle photographs. He strongly favours the possibility that long range Coulomb forces operate against two particles coming close together, thus preventing coincidence altogether. However, Pisani and Thompson (1971) provide some evidence of the Poisson distribution. Their work stemmed from the paper by Edmundson (1968) which described a dead time after each particle count, during which no further particle could be registered. From the constant scanning of the aperture Pisani and Thompson (1971) found that the timing of the particles reaching the aperture followed a Poisson distribution. If such evidence for the Poisson distribution is sound then there is the basis for further study of the type of occurrence of coincidence, and for corrections to be made. However, when ASTM (1971) made some coincident corrections they found them to be insignificant.

Without an acceptable answer to the problem, every care has been taken in this study with dispersion techniques and correct concentration to minimise the coincidence of particles in the aperture.

4.4.2. Accuracy.

"Accuracy" in the present context has been defined, by the Inter Agency Committee on Water Resources (1964) and Allen (1968), as the counting of the true particle size distribution. With the variety of measuring techniques available, largely measuring different parameters, the particle parameter evaluated must also be clearly defined for the size distribution to be meaningful. This is particularly important since the results of different parameters cannot be simply compared.

Sheldon and Parsons (1968) considered microscopic sizing to be the most absolute measurement but the electronic counter does have a high statistical accuracy according to Giever (1976) and the manual (Coulter Electronics 1978).

The problems in producing results of absolute accuracy with the Coulter Counter lie in its design. The particle size distribution is one of particle volumes, or spherical-equivalents of the particle diameters, passing through the aperture which has a tendency to over-read as described above. According to the manual (Coulter Electronics, 1978) there is an acceptable level of accuracy even ignoring coincidence errors and background noise, which together total 1%, particularly when ± 2% error has been attributed to sampling.

The question of background noise, or the reduction of accuracy at the fine end of the distribution, has been discussed by Shideler (1976). The background counts from the "blank" electrolyte can be subtracted from the count of the fine particles but gives little significant improvement. Shideler (1976) found that a high degree of accuracy and precision was too difficult to maintain for tube size of less than 30µm without losing the advantage of rapid analyses.

4.4.3 Precision.

The precision of the instrument was found to be good as long as a sufficient number of particles were counted. Sheldon and Parsons (1967) and Walker and Hutka (1971) found some random variation of particle size around the mean of each sample but showed that the variation decreased with the number of particles counted. 1000 particles were considered by both pairs of authors to give good precision in the results. The stormwater sediment count per sample was in the order of 200,000 thus random variation is negligable providing the low concentration rate is maintained. The count rate has been considered important in this context by some authors; Sheldon and Parsons (1968) and Giever (1976) suggested that the count rate should not exceed 4000 to 5000 counts per second particularly for apeetures smaller than 50µm.

Microscopic sizing is generally considered to produce absolute measurements of particle diameter. The precision of the electronic counter has to be gauged by comparing the results from the two methods. Walker and Hutka (1971) and Giever (1976) found a 1:1 correlation between the results from the microscope and electronic counter for glass spheres of 5 to 30µm diameter measured with a 100µm aperture. In natural sediments the diameters measured by each technique may differ more noticeably because irregularly shaped particles will tend to be over-sized by the electronic counter. Random measurement of stormwater sediments under the electron microscope confirmed the particle size range measured by the electronic counter and a detailed correlation was not necessary.

In the light of the close correlation between electronic counter and microscope results Giever (1976) went so far as to suggest the electronic counter would make a successful and much less arduous substitute to microscope counting. This may indeed be so as Wood and Lines (1966) have shown that results obtained from the electronic counter were independent of operator error and ASTM (1971), on results from several laboratories, showed that intra-laboratory analyses by the same operator gave results for all particle sizes of $\pm$ 1% precision, at the 95% level of significance, and inter-laboratory precision was similarly calculated at $\pm$ 3%. For the stormwater sediments the methods was sufficiently sensitive, and the results sufficiently precise, to show changes in the size distributions of successive samples.

4.4.4. Reproducibility.

All the authors using the electronic counter found a high standard of reproducibility. As mentioned above the results have been shown to be independent of operator error and Sheldon and Parsons (1968) found the high degree of reproducibility was also independent of aperture size and sample volume. The size of the count does however appear to affect reproducibility as found from the more erratic counts of low concentration (5 to 10%) stormwater particles and as described by Kellie (1966). However, providing the factors mentioned of thorough dispersion and the maintainance of the correct calibration were ensured, the degree of reproducibility should remain high. A number of stormwater samples were repeatedly analysed to demonstrate the reproducibility of the method and there was no significant difference between the results, as is shown in Figure 4.1.

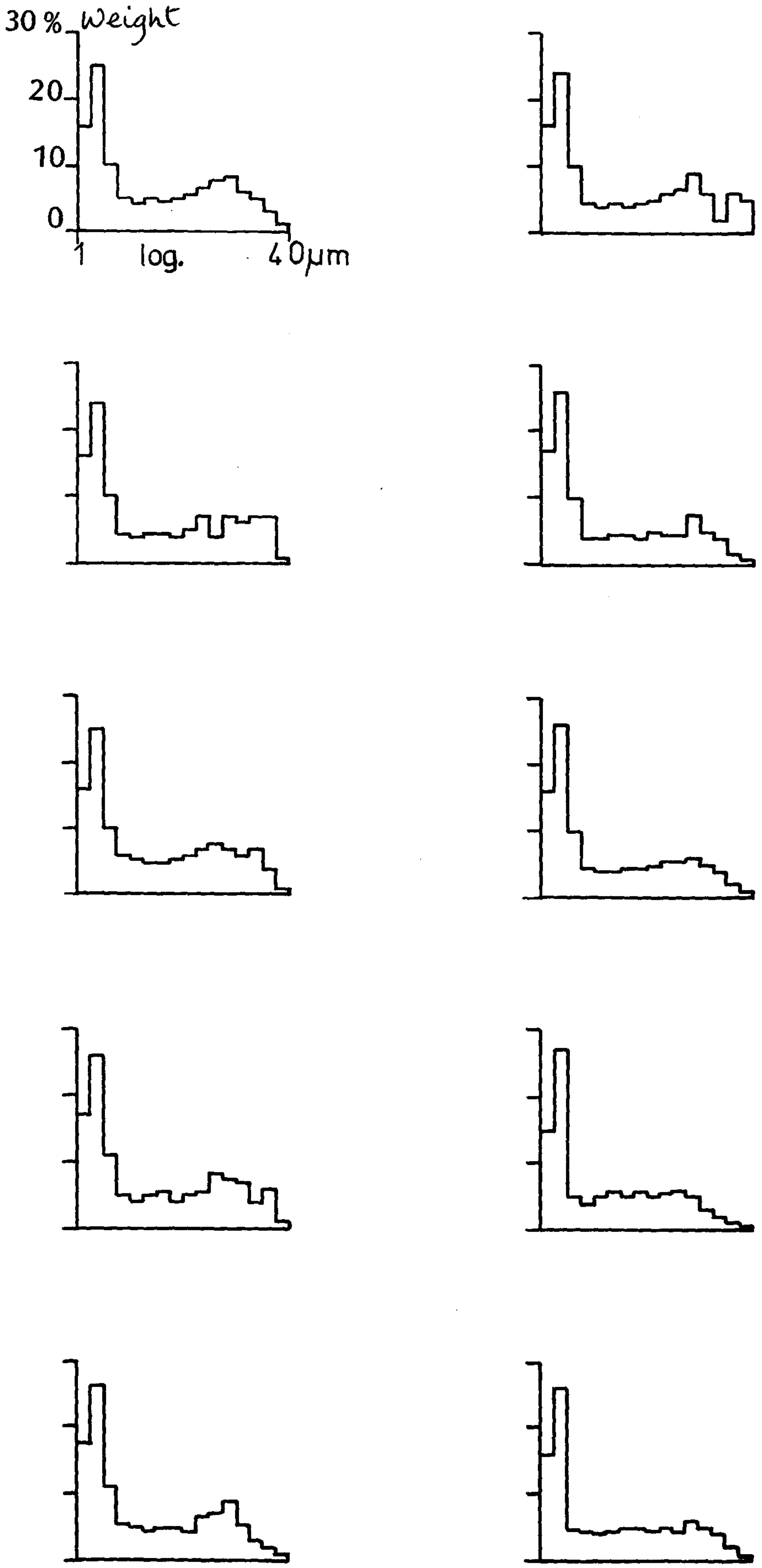
4.5. A Comparison of the Electronic Counter with Mechanical and Optical Particle Measuring Techniques.

4.5.1. Introduction.

A study of particle size analysis would not be complete without a mention of techniques other than electronic counting. Sieving,

FIGURE 4.1.

REPRODUCIBILITY OF SIZE CURVES.



sedimentation and pipette methods of measurement have been widely discussed in the literature and, increasingly, optical sensing methods are being perfected.

The choice of technique depends largely on the size range of the sediment in question. Sieves cater for sediment from cobble size (approximately 50 to 100mm) down to less than 30µm, although they often are not very effective below 63µm, whereas settling tubes and the pipette measure fine sediment approximately from 1 to 10µm and electronic counting and optical methods are capable of monitoring down to less than 0.5µm.

A second priority in the choice of technique is equally important that is, what parameters are required, or which parameters of the sediment it is possible to measure. The various techniques measure different parameters, for example particle volume, settling velocity and, in irregularly shaped particles, a number of different specified diameters.

4.5.2. Sieving.

Zwicker (1967) compared particle size techniques to find a method best suited to the requirements of the ceramic industry. For sediment greater than 40µm, sieves provided the most appropriate measurement method. Dry sieving, involving machine shaking with an air jet, was both the most effective and the cheapest use of the sieves. Wet sieving was used for very fine or 'sticky' particles and gave precise results but was too slow for routine use.

Sediment less than 40µm had to be accurately measured by a technique which gave results comparable with the coarser results. Micro-mesh sieving provided such results and covered a size range of 1 to 600µm with good precision but poor reproducibility. By comparison, electronic counting gave reproducibility results in good agreement with those from sieving but in early models only provided a lower limit of 2µm. At that time the electronic counter took as long for samples to be analysed as by sieving and the cost weighed heavily against the technique. A major technical disadvantage of the then current electronic counter for this study was that the results for the extreme ends of the distributions had to be extrapolated which was not sufficiently accurate. Walker and Hutka (1971), working with soils in the size range 37.2 to 88.5µm, found the results from the Coulter Counter higher than those from sieving. Microscopic examination showed a discrepancy in mesh apertures of up to 10%. A good linear relationship was found between sieves and Coulter Counter data although the exact relationship varied with each set of sieves. In conclusion, they found the Coulter Counter has the advantage of speed and accuracy over the other methods.

Kiff (1973), in a thorough study of comparative particle size techniques, covered the size range 0.1 to 100µm but concentrated on sieving for the coarser material and produced the size distribution from more than one method. Shideler (1976), pointed out the significant abrasion and breakdown of soft particles during sieving which resulted in under-reading.

4.5.3. Settling Tube.

Emery (1938) and the U.S. Bureau of Reclamation and associated bodies (1942) provided some of the earliest studies of the settling tube, based on Stoke's Law, for particle sizing. The settling velocity was the parameter measured, the main drawback of which has been its incompatibility with other size parameters. In 1938 the method was new and provided a relatively rapid analysis of sands whose settling velocities were measured after successive predetermined time intervals. The advantages are in the gravitational settling procedure which can be simulated in the native water of the sediment sample providing the confined tube space does not lead to particle flocculation. A major disadvantage of the method, described by Lines and Wood (1965), is the presence of convection currents which prevent the settling of material up to 4µm. With an increase in temperature larger particles were held up or re-entrained.

The method of centrifugal sedimentation was explored by Zwicker (1967) who found it was precise and independent of operator error although only suitable for sediment of 20μm or less. The degree of precision was reduced with sediments of mixed densities and where larger material was initially removed by sieving the final size distribution was distorted. Here again the Coulter Counter compared favourably apart from the cost involved.

Kiff (1973) preferred the sedimentation technique to the Coulter Counter and, used in combination with sieving, covered a substantial size range. With practice, operator error was reduced to an insignificant level and there was the advantage of analysis of the sediment in near-natural conditions. Kiff (1973) also found the Coulter Counter overread.

Guy (circa 1976) found a number of disadvantages of the settling tube. The effect of a falling particle was to displace neighbouring particles and a locally high concentration of particles caused artificially high settling velocities. Further he found varying particle density to be a problem and that in river water the formation and disaggregation of flocs also altered the settling velocity.

4.5.4. Pipette

In 1968 Allen (1968) concluded from his comparison with the pipette method that electronic counting was probably the most accurate technique for routine particle analysis. However he found the Coulter Counter produced coarser results than the pipette for the same sample owing to: the smaller upper size limit of the Coulter Counter, the coincidence error, and the shape factor, particularly with the finer particles where the discrepancy widens. However, manipulation of both sets of data showed the difference was insignificant.

The Coulter Counter was also preferred to the pipette by Walker and Hutka (1971) who pointed out that whereas the pipette provides cumulative-weight percentage data, the Coulter Counter gave the more useful cumulative number percent, or volume, which can be related to weight.

Shideler's (1976) main reason for preferring the Coulter Counter was the 30 minutes preparation time compared with the 24 hours required for pipette analysis and the fact that the pipette apparatus is susceptible to diurnal temperature changes. Shideler (1976) made the useful point, that has been mentioned above, that the previous literature was comparing various methods with the older models of the Coulter Counter. The more recent models, measuring from 0.5µm, have sixteen size channels, population accessory and plotting and printout facility, and can analyse each sample in 30 seconds.

With the pipette method, as well as the settling tube, Guy (circa 1976) found fine sediment remained in suspension in the convection currents.

Behrens (1978) compared the electronic counting and pipette methods in some detail and concluded that the difference in grain size distribution from the two was the result of the Coulter Counter not measuring the fine clay section, a factor attributed to the lower standard deviations of the Coulter Counter data. However, despite omission of data on particles of less than 0.5µm, the Coulter Counter would still provide a fuller size distribution than the pipette method which suffers from convection preventing measurements under 3 to 4µm. It must be surmised that Behrens (1978) is using a much older model of the Coulter Counter than his date of writing would suggest. However, further results for slightly coarser sediment show the Coulter Counter produces finer results than the pipette. Values of skewness and kurtosis derived from the two distributions are very similar. In his conclusion Behrens (1978) still stresses the need to know exactly what parameters are being measured.

4.4.5. A Note on Optical Techniques.

Kiff (1973) reveiwed an early photic method in which particles settled through a liquid with constant scanning of particle diameters by a light source. The results suffered from particles of greater densities settling out differentially.

Giever (1976) described more fully a system in which a photic sensing zone detects the passage of particles by forward and sideways light scattering or by shadowing. Together, the photic zone and sensor are formed by an optical system. Particles are in suspension in a gas or a liquid, the minimum particle size being 0.2 to 0.4μm in gases and 3 to 5μm in liquids. It should be noted here that at this stage the Coulter Counter still had the advantage in analyses in liquids for fine particle size measurements. The upper size limit for particles in gas ranged from 19 to 70μm. The size range is large as the settling velocities depend on particle density and no agitation can be provided to prevent settling. The gas system is sensitive and can be used to measure airborne particles without the inherent problems of putting them into solution. If the particle concentration is too great a secondary scattering of light interferes with the results which at this stage was fairly difficult to interpret.

4.5.6. Conclusion.

The conclusions to be drawn from the comparative studies are that, for the corresponding size ranges, sieving tends to under-read, and the electronic counter to over-read. However, other advantages have been shown to make electronic counting preferable to the pipette method and to the settling tube technique whose results are so difficult to compare with other methods. Optical techniques are still in their infancy and there too the exact parameter measured must be evaluated. The advantages of the Coulter Counter and its suitability for measuring stormwater sediments in their native water make it the best choice for analysis in this study.

CHAPTER 5

THE CHANGING PATTERNS OF SEDIMENT SIZE DISTRIBUTIONS DURING STORMFLOW.

5.1. Introduction.

The method of measuring particle size has been described in the previous chapter and the results are now examined and put in the context of sediment availability and the prevailing hydrological conditions. The changes in particle size patterns are observed along the route taken by the sediment in runoff, from the origin, across the land surface into the drain and then during drain flow to the outfall. A detailed examination is then made of the size variations of the sediment collected at the outfall during different types of storms and contrasts are made between storms.

The quantity of sediment available for entrainment on the land surface depends partly on the antecedent conditions (discussed in Chapter 3) although it is also determined by such factors as: the nature of the land surface and its weight of traffic, the seasonal effects of plant debris, and the frequency and efficiency of street cleaning (Ellis and Revitt, 1980). The sediment comprises individual particles whose sizes depend on their origin and transport history. The origin of the sediment can be divided into three main categories, that derived from buildings and from roads and that carried by air. The fine, often spherical, airborne sediment includes dust, flyash and products of combustion from industry and vehicles. This sediment is washed out of the atmosphere by rainfall and collected in road and roof gutters where it joins material, including clay minerals weathered from roofs and buildings. Road sediments comprise coarser and relatively more durable sediment which is the product of granitic and limestone roadstone erosion, and finer particles from concrete road surfaces. Road sediment also includes particles from vehicles, for example rust, paint and rubber, and from surface runoff from adjacent land use areas. Any soil particles or fragments of vegetation from gardens and open spaces are collected in road runoff as they reach the gutters (Ellis, 1976). In heavy storms through-flow as well as surface runoff can be seen washing soil into nearby road gutters (Neville, 1974). The quartz particles of the road sediment are by far the most resistent to chemical and physical erosion during surface runoff and drain flow and in consequence they form the largest proportion of the sediment that reaches the outfall. In addition, they include the largest particles sampled (up to 40μm) which is probably also a result of their resistance to erosion. Other particles of roadstone such as feldspars and micas, clay minerals from building bricks and roof tiles, and airborne particles all occur in much smaller quantities than quartz and are more susceptible to erosion during stormwater transport.

As the sediment passes through the system from land surface to outfall it undergoes progressive aggregation by silica cementation as described in Chapter 3. Aggregation begins on the surface if the particles go through a period of stationary or slow moving water but occurs to a much greater extent in the drain during stormflow and in the decreasing discharge after sediment deposition. It is helpful to remember here the importance of the process of aggregation by silica cementation because it explains to a considerable extent the form of the size distributions. The sediment size distributions sampled during storms are either bimodal, unimodal or a mixture of the two. Most frequently the individual particles dominate the fine end of bimodal distributions and the coarse sediment is dominated by aggregates. During high intensity rainfall however coarser particles than usual can be entrained from the surface and as any previously deposited aggregates are rapidly removed the individual particles form a unimodal size distribution which covers almost the whole of the range sampled (1 to 40μm).

The size curves are described in detail and an attempt is made to explain the changing forms by reference to hydrological characteristics, in particular discharge fluctuations and the effects of initial high rainfall intensities, and the likely availability of sediment resulting from the antecedent conditions. These hydrogical parameters help to explain the site variations observed both during individual storms and between storms, and the variations found along the storm drain.

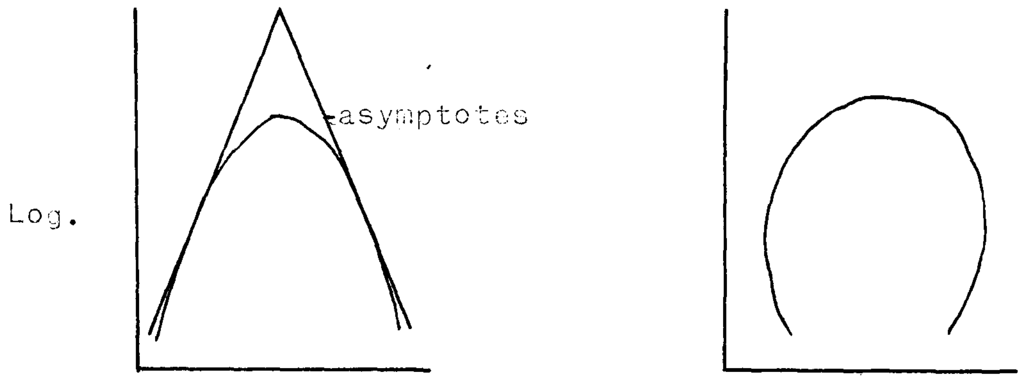
5.2. Statistical Treatment of Particle Size Distributions.

The size distributions of natural sediments have for a long time been recognised as a continuum represented by a smooth size curve (Krumbein,1934). The log-normal curve was found to be a good approximation to many size frequency curves as has been demonstrated with different sediment size fractions by a number of authors, for example, Udden (1914), Folk and Ward (1957), Rogers (1959) and Visher (1969). Negative exponential functions have also been used to describe grain size distributions, for example Krumbein (1937) demonstrated the usefulness of the method in the study of particle size reduction with increasing distance of transport.

Bagnold (1937) found that size measurements for wind blown sand followed most closely a hyperbolic distribution. The data were examined on a log-histogram plot by Bagnold and Barndorff-Nielsen (1980) and were found to describe a hyperbola rather than a parabola. A parabola would have been formed if the data had followed a normal distribution as has been suggested by other authors. The normal distribution is seen as just one case of the hyperbolic distribution (Barndorff-Nielsen, 1977). Sands from similar environments each conform to similar size distributions of which some are normal, whereas sand size distributions from various environments deviate from each other but all conform to the hyperbolic distribution. Thus the data are considered as a mixture of normal distributions and others but all of them are hyperbolic (Sichel, 1973; Barndorff-Nielsen, 1977 , 1979; Deigaard and Fiedsøe, 1978; Bader, 1970).

FIGURE 5.1.

CONTRAST BETWEEN HYBERBOLA AND PARABOLA.



Log.
Hyperbola

Parabola

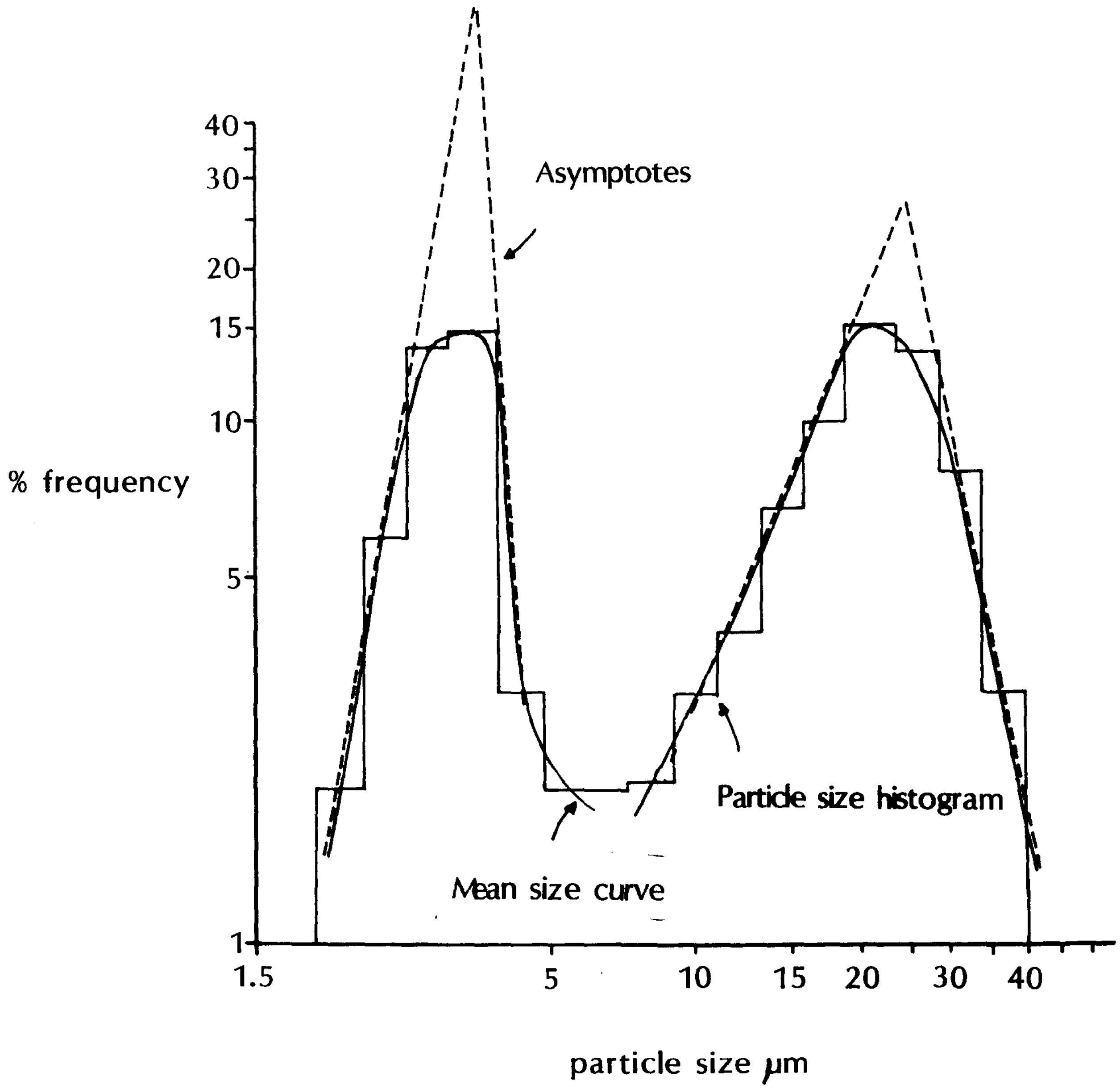
Figure 5.1 shows the contrasting shapes of the hyperbola and the parabola. It is interesting to note that when the example of the fine distribution of storm sediment (Figure 5.2. storm of 6.10.80. Sample 1) is plotted on log-log axes the curve appears to follow the same pattern as the hyperbolic distribution. (Bagnold and Barndorff-Nielsen, 1980). The right-hand side of the coarse distribution would also appear to conform to this pattern but the negatively-skewed nature of the distribution confuses the issue on the left-hand side.* Because of the more relevant need here to describe the bimodality of the distribution as a whole this discussion is continued in Roberts (Middlesex Polytechnic Internal Report, in Press).

The absence of part of the sediment size range and the mixing of two or more sediments of different modal sizes produce truncated and segmented or polymodal size curves respectively.

*** The parabola omits the tails which are important, and for which the log-log scale was introduced so that equal significance would be attached to all sizes. The hyperbola and its parameters take into account the tails.**

FIGURE 5.2.

THE RELATIONSHIP BETWEEN A SAMPLE PARTICLE SIZE DISTRIBUTION AND THE HYPERBOLIC CURVE



Polymodal size curves are most commonly considered to describe a sediment sample which is either of multiple source (Mason and Folk, 1958) or the result of more than one mode of transport or energy level of depositional environment (Visher 1969; Sagoe and Visher, 1977). Where sediment transport appears the most likely cause the influence of the sediment source should not be overlooked (Ashley, 1978); any reduction in particle size from the source should be related to the durability of the mineral (Sagoe and Visher, 1977) and to the distance and mode of transport. The individual components of polymodal size curves are usually assumed to be normal distributions by these authors, but Walton, Stephens and Shawa (1980) pointed out the likelihood of truncation resulting from the loss of part of a size range with the mixing of more than one sediment type.

The particle size distributions of the stormwater sediment were one of three types : unimodal, bimodal, or a mixture of the two; the bimodal curves occurred in the majority of storms. Such studies as there are specifically on bimodal distributions follow analyses of polymodal distributions in attributing the different mode of the size curves to either source (Folk and Ward, 1957; Binda and Hildred, 1973); or to transport, for example suspension and traction (Middleton 1976); or to a deposit comprising grains within a finer grained matrix (Spencer, 1963; Hollister and Heezen, 1964)

The size frequency data in the present study on sediment size distributions comprised a numerical printout and histograms of differential and cumulative volume, and the total number of particles counted. The size range was divided into sixteen classes on a logarithmic scale with intervals of multiples of $\sqrt[3]{2}$ (Allen, 1968, 1972; Coulter Electronics 1978). The frequency was measured as a percentage of the total number of particles.

In the literature there is little comprehensive analysis of bimodal curves as a whole, rather they are treated statistically as two normal curves.

The bimodal size distributions of the stormwater sediment were treated as two individual curves because in the majority of samples the two sections of the size curve represented sediment in two different forms (observed in microscopic examinations described in Chapters 7 and 8). The distribution at the finer end of the size range represented the individual particles and the curve at the coarser end represented the aggregated particles. The division between the two was made after visual inspection of each distribution. The finer sediment curve consistently followed a normal distribution within the range 1 to 3μm. The upper limit could be extrapolated accurately by eye to complete the distribution where necessary as for example in storm 14.11.80 (Figure 5.11) at the overlap with the coarse distribution, or where the fines are truncated as in storm 16.11.81. (Figure 5.7).The size fraction 3 to 40μm, a negatively-skewed distribution, was similarly straightforward to extrapolate. Often the fine tail of the coarse skewed size curve accounts for sediment sizes of approximately 3 to 5μm. Occasionally however, the size curve deviates slightly in this region to include a minority of particles which are either moderately coarse individual particles entrained from the surface and not yet incorporated into aggregates, or possibly, very small aggregates in the early stages of development.

In the context of segmented and truncated polymodal size curves the fine and coarse fractions of bimodal curves comprise respectively the individual and aggregated particles (Chapter 7). With the low percentage of particles of sizes between the modal fine and modal coarse values, the size curves, and especially cumulative curves, can be said to represent segmented or polymodal sediment distributions. In fact this is the same sediment in two different states due to aggregation processes active in the drain which create two size distributions. Unimodal curves describe a more normal range of particle sizes when coarser sediment is available as a result of intense rainfall and when all particles are individual, aggregation having not yet occurred.

A few authors have attempted to analyse bimodal curves in their entirety by allotting skewness and kurtosis values to the curve (Inman, 1952; Folk and Ward, 1957; Spencer, 1973; Ashley, 1978). Ashley (1978) suggested that skewness and kurtosis could be used to reflect the magnitude and separation of the component populations. Similarly, Folk and Ward (1957) and Spencer (1963) suggested skewness and kurtosis described the degree of truncation and sorting. However judging by the stormwater results this appears to be a rather negative use of both skewness and kurtosis as they are measures designed to describe the modal size range and peakedness of single mode curves (Bulmer, 1967; Briggs, 1977). Their application to two well-separated peaks provides poor values of each and detracts substantially from their meaning. Moiola and Weiser (1968) found mean and standard deviation more useful differentiators of different sediments. For each stormwater sediment size distribution the mean, standard deviation, skewness, kurtosis and percentage sediment were measured for both fine and coarse components of the bimodal curve and for the unimodal curves, the process was simplified by analysing the data on the computer. The results are described and discussed in the following section.

5.3. The Influence of Land Use on Sediment Size Distributions.

Sediment samples were taken from the various catchment land uses with the aim of establishing the size range and form of the distributions to aid, in conjunction with the surface texture studies of Chapter 7, the investigation of stormwater sediment source and transport history. Sediment was collected in stormwater runoff from gutters in each land use area shown in Figure 2.1.

The samples are listed in both Figure 5.3 and Table 5.1 in their successive order down the gradient of the catchment. The drainage network is intensive and it is unlikely that sediment from one land use area could travel very far into an adjacent one. This is borne out by the distinct individuality of the different land use size distributions.

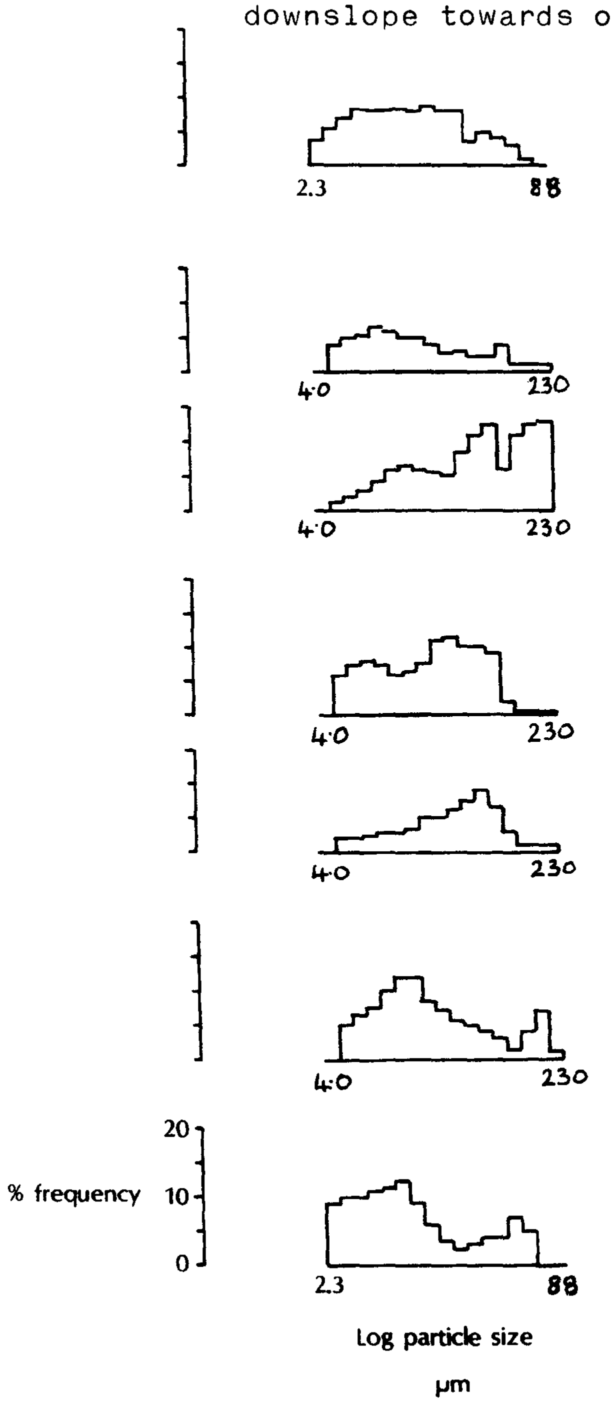
The size distribution of Sample 1 (Figure 5.3.) from the head of the catchment is determined by the aggregating effect on the sediment by silica available from the abundance of concrete in driveways in the area (Hobbs, 1980). The distribution appears to be bimodal with modal frequency peaks from 5 to 20µm and at 40µm. From the evidence of the photomicrographs (Chapter 7) there is an abundance of aggregates in this sample which cover almost the entire size range. Only a small proportion of individual particles were seen and it can therefore be assumed that aggregates form quickly as soon as constituent particles are available. A unimodal size range of aggregates might then be expected, perhaps with a continuation of the curve below 2.3µm and with a small frequency peak of fine particles. In the size curve for this sample on Figure 5.3 a point of division can be seen at 30µm. No obvious explanation was found for this. The sample was rerun over the larger size range of 4 to 230µm and no such anomaly occurred; the wider size range does however create some loss of detail. If this point of division is significant the curve above 30µm may represent sediment of a different nature.

Sample 2, Figure 5.3, was taken from an area of new housing with small gardens. 85% of the distributions are positively skewed and predominantly of fine sediment with peak frequency at 9µm. The smaller, coarser fraction of the sediment, peaking at 90µm can be assumed to be aggregates washed from the soil (discussed further in Chapter 7) while the finer fraction denotes individual particles of housing material.

FIGURE 5.3.

LAND USE PARTICLE SIZE DISTRIBUTIONS

Listed in order from head of catchment downslope towards outfall.



Sample 1
Modern Housing, concrete drives.

Sample 2
Modern housing.

Sample 3
Bricked shopping area

Sample 4
Open space, soil

Sample 5
Modern housing, without gardens.

Sample 6
Old housing.

Sample 7
Commercial traffic, Aerodrome Road.

TABLE 5.1.

SIZE DISTRIBUTION PARAMETERS OF LAND USE SAMPLES.

Sample	Distribution	%	Peak size μm	Mean μ %	Standard deviation σ
1. Head of Catchment	fine coarse	16 84	5-20 40	3.2 6.9	1.8 3.2
2. Two-Storey New Housing	fine coarse	85 15	9 90	4.2 1.6	1.3 1.4
3. Shops	fine coarse (i) coarse (ii)	39 34 36	16 75 210	4.3 9.1 9.6	1.8 3.1 3.0
4. Open Space	fine coarse	35 65	7 34	6.9 9.0	0.9 1.9
5. New Housing	unimodal	100	57	3.7	2.3
6. Old Housing	fine coarse	89 11	11-17 160	6.4 3.7	3.2 2.8
7. Commercial Traffic	fine coarse	78 23	8 49	10.1 3.7	4.3 2.1

The complex trimodal distribution of Sample 3 (Figure 5.3) is difficult to explain. The sample was taken from within a shopping area where both shops and walking surface were composed of one type of brick. The area was pedestrianised and thus devoid of cars but occasional islands of vegetation would have provided soil particles although of a very small percentage compared with the brick material. The distribution of fine particles can be attributed to eroded fragments as seen in the micrographs. The coarser two distributions may describe two major constituents of the brick-clay particles which cover the size ranges 39 to 84μm and 110 to 230μm respectively. Alternatively, more rapidly eroding soil particles may generate the fine and moderate distributions and the bricks account for the coarsest. The form of soil particles (Sample 4) is represented in Figure 5.3 and comprises both fine individual particles and relatively large well-structured soil aggregates. Both sides of the distribution are broadly spread around modal sizes of 7μm and 34μm respectively, (Table 5.1)

The sediment size from the area of new housing lower down the catchment (Sample 5) is described by a slightly positively skewed unimodal distribution of modal size 57μm. The houses are terraced with small courtyards but no gardens and are surrounded by access roads and garage areas. The sediment consists of individual particles which have been rapidly washed from the buildings to the drains without time to aggregate and without any input from soil aggregates.

Aggregates are once more included in the bimodal distribution of the sediment collected from the area of old Victorian and inter-war housing with large gardens and with a heavily used road through the area (Sample 6). The fine sediment makes up 89% of the total size distribution curve due to a dominance of road, traffic, and building material, while the remainder comprises soil aggregates and some stormwater aggregates (shown in Chapter 8). The aggregates appear to be formed from weathered and eroded road and building surfaces which provide the sediment and silica for aggregation.

Heavy commercial vehicles form the majority of the traffic along Aerodrome Road (Figure 5.3 Sample 7) which is towards the southern and lowest-lying part of the catchment and serves a variety of storage yards. 77.5% of the distribution is between 2.3 µm and 27µm and the remainder reaches 180µm. The area is relatively level with surfaces of roadstone and concrete. The heavy wear and tear generates fine sediment constantly and the combination of available silica from eroded surfaces and slowflow over level surfaces would allow for the formation of stormwater aggregates before entry to the drain.

In conclusion, it has been shown that the sediment from all samples (with the possible exception of Sample 3) comprises a mixture of fine individual particles and coarser aggregates. Figure 5.3 shows clearly aggregates occurring where they would be expected; from soil runoff, or in conditions of rapid formation in stormwater (Sample 1). Conversely, there is a much lower proportion of aggregates in Sample 5 where there is no access to soil material. The results show the most likely size distributions for each land use and display such details as the effects of concrete drives and unimodality where ready-made soil aggregates are absent. The results are reproducible, and distinguish the different land use areas.

5.4 Sediment Size Variations Along the Storm Drain.

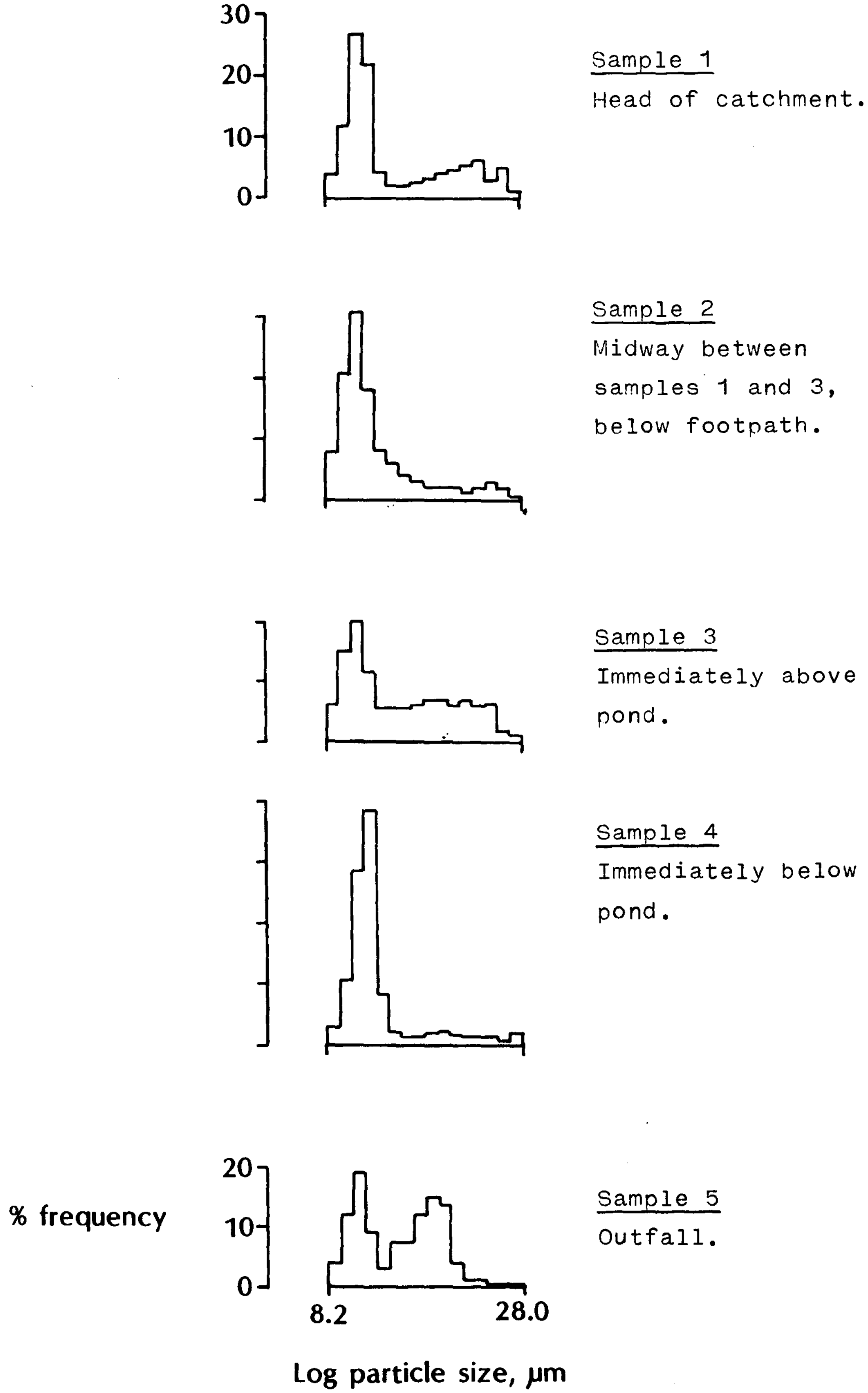
A considerable size range of sediment is found throughout the length of the drain. It is the result of the continual input of sediment in stormwater from the surface and from the network of contributory drains. The nature of the sediment varies according to the type of land use and is further altered by the stormwater transport. As is shown in Chapter 7, some alteration, by abrasion and silica precipitation and solution occurs on the surface in gutter stormwater but the greatest degree of alteration is caused by drain transport. The system of sediment collection and transport is thus complicated making it difficult to draw clear conclusions from the analysis.

Sediment freshly introduced into the drain comprises separate particles which become cemented together by precipitated silica to form aggregates (Chapter 7). The size curves are thus bimodal with fine and coarse fractions which represent the individual and aggregated particles respectively. This being the case the two curves are most clearly analysed separately. Any attempt at producing average values invalidates the data. The results calculated of percentage, mean and standard deviation for each sample are shown in Table 5.2. The size curves for the fine sediment are normally-distributed over a small size range while the coarse curves are negatively skewed over a wider range.

The contrasts in size distributions along the drain are shown in Figure 5.4. Sample point 1, at the head of the catchment, collects fairly homogeneous sediment from only one land use type. The process of progressive alteration of this sediment could be expected to begin at this point and to continue downstream. However, the land use is modern housing with concrete driveways which is described in Section 5.3 above. As a result the silica content in the runoff is relatively high and creates significant aggregation (32% of the sediment entering the drain, Table 5.2). The proportion of aggregates has diminished considerably (8%) by the next sample point due to the effects of dilution which increase with distance downstream. Sample point 2 occurs beside a footpath across a grassed area mid-way between Sample points 1 and 3 and is dominated by fine individual particles (Figure 5.4). Particle size increases again as far as Sample point 3. This might be expected as both the input of sediment and the availability of silica for aggregation increase with distance downstream. The increase in the coarse fraction is shown clearly in Figure 5.4 and forms 42% of the distribution (Table 5.2). Between Sample points 3 and 4 however is the settling pond where a very

FIGURE 5.4.

PARTICLE SIZE DISTRIBUTIONS ALONG THE DRAIN



substantial quantity of the sediment settles out. This can be seen by the fall of coarse material to 11% (Table 5.2) and the predominance of fine particles remaining in the flow (Figure 5.4). A comparison of the percentages of Samples 2 and 4 (Table 5.2) shows that although the settling pond allows almost 90% of the aggregates to settle out the situation below the pond is not returned to that of the early stages of the sediment transport.

After travelling this far in the drain all but the most recently introduced fine particles have been altered by silica precipitation on their surfaces. The process is considerably hastened by the slow-flow conditions of the pond. Thus the sediment carried downstream from the pond comprises individual fine particles coated with precipitated silica. However the expected development of aggregates is once again restored as the sediment travels downstream to Sample point 5 where aggregates dominate the size distribution (Figure 5.4, 56%, Table 5.2). The effect is increased by the confluence of the drain with a second main branch sewer which has no settling pond and thus contributes a high proportion of aggregates.

The percentages of coarse sediment are shown in Figure 5.5, with the scale distance along the drain, which clearly demonstrates the changing form of sediment as it is transported along the drain. In the first section between Sample points 1 and 2 the effect of dilution in progressively reducing the proportion of aggregates along the drain is relatively rapid and shows that the effect of the silaceous concrete input in creating aggregates is extremely local. The effects of the settling pond in allowing the aggregates to settle out of the flow are very marked and are clearly shown in Figure 5.5. The process is however limited to the small area of the pond and only temporarily interrupts the overall increase in aggregates with distance downstream. The trend of increasing aggregation is renewed between the pond and the outfall. The rates of progressive alteration are similar between Samples 2 and 3 and between Samples 4 and 5. The rate of alteration is slightly lower between Samples 4 and 5

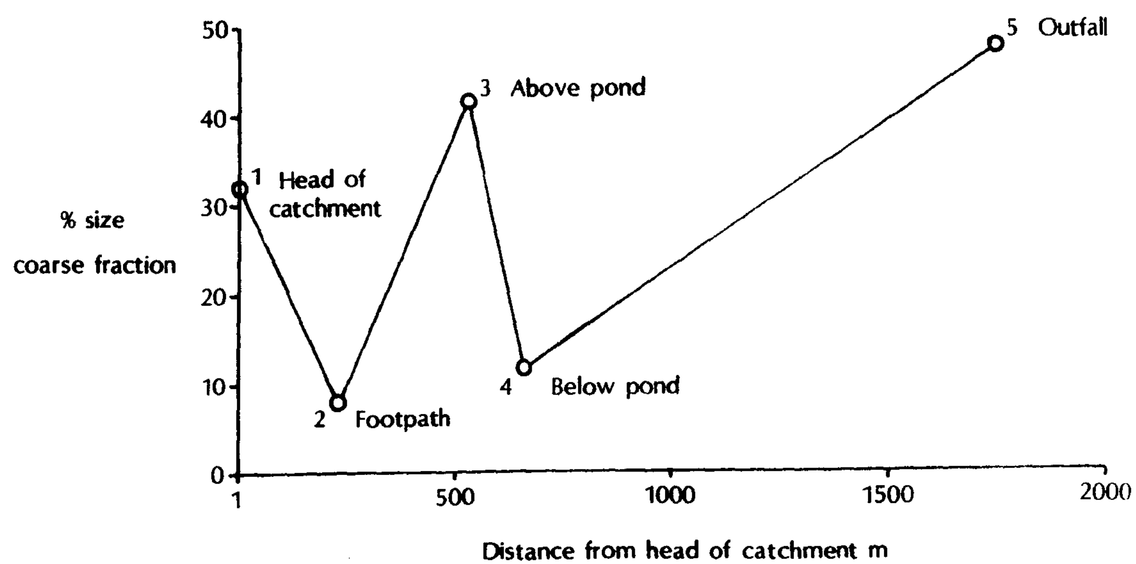
TABLE 5.2.

SIZE DISTRIBUTION PARAMETERS OF DRAIN SAMPLES.

Sample	Distribution	%	Peak μm	μ	σ
1. Head of Catchment	fine coarse	68 32	1.4 13.0	1.5 11.0	0.3 5.9
2. Sample midway 1-3	fine coarse	92 8	1.4 16.0	2.0 15.6	1.3 3.6
3. Above Pond	fine coarse	58 42	2.0 9.5	2.4 10.9	1.0 5.0
4. Below Pond	fine coarse	89 11	1.8 7.0	1.6 11.1	0.3 6.8
5. Outfall	fine coarse	45 55	1.4 5.3	1.4 5.3	0.3 1.8

FIGURE 5.5.

SEDIMENT SIZE VARIATIONS DOWNSTREAM ALONG DRAIN



which may seem surprising since the adjoining sewer provides a high proportion of aggregates between points 4 and 5. It indicates that, at least at the time of sampling, the effect of dilution of incoming stormwater is slightly greater than the effect of additional aggregates over this section.

5.5. Variations in Size Distributions During a Storm.

5.5.1. Factors Influencing the Sediment Size Distributions.

The sediment sampled automatically throughout storms at the outfall varies in its proportions of fine and coarse particles during each storm. The size of the sediment reaching the outfall in stormwater depends both upon the size of the sediment available for input on the surface and on the discharge and carrying capacity of the water. It is useful here to note the pertinent features of the results from the hydrological observations discussed in Chapter 3. A dry period of at least 150 hours between storms seems to be required for the accumulation of sufficient surface sediment to influence the pattern of particle size distributions through storms (Table 5.3); the longer the period the more sediment is available and the larger the particles it includes. The preceding storm type determines the quantity of sediment left in the drain; storms of Groups I and II tend to flush the drain clear of sediment whereas those of Groups III and IV and sometimes of Group II, deposit sediment during their falling discharge, which becomes aggregated. With the gradual onset of rainfall fine particles will be the first sediment to be entrained. However if coarser sediment is readily available the runoff from Group I storms, with initial high intensity rainfall, will entrain it from the beginning. These storm sediment size curves will thus be dominated in the early stages by coarse sediment. The hydrological characteristics similarly affect the sediment size pattern at the end of the storms. The sudden cessation of rainfall and the rapid fall in discharge of Group I storms will

TABLE 5.3

ANTECEDENT CONDITIONS INFLUENCING STORM SEDIMENT SIZE DISTRIBUTIONS

Storm	Size Distribution	Antecedent Dry Period Hrs	Antecedent Drain Conditions *
Group I 7.10.80	mixed	11	clear/fines
5. 5.81	unimodal	56	clear
1. 6.81	unimodal	181	sediment
11. 9.81	unimodal	20	coarse
14. 9.81	unimodal	55	clear/fines
18. 9.81	unimodal, mixed	75	fines
16.11.81	unimodal	398	sediment
Group I/II 17.11.81	mixed	11	clear
Group II 10. 7.80	bimodal	105	sediment
6/7.10.80	bimodal	381	sediment
10.10.80	bimodal	75	coarse
3. 5.81a	unimodal	150	sediment
19.10.81	mixed	111	fines
Group III 14.11.80	bimodal	179	sediment
30. 3.81	unimodal	42	sediment
10. 9.81	bimodal (unimodal)	505	sediment
7.12.81	bimodal	275	sediment
Group IV 8/9. 7.80	bimodal	112	sediment
17. 3.81	unimodal	63	clear/fines
26.11.81	bimodal	169	fines

* As accurate as possible based on previous storm type and antecedent conditions.

produce size distributions dominated by coarse sediment during all but the last few minutes. The exception to this occurs when a high discharge has been sustained long enough to exhaust the drain of sediment leaving very little to be sampled in later discharge as in the storms of Groups I and II and in particular in the storms of extremely high rainfall intensity of long duration. However, the more usual, slow decrease in discharge allows for the gradual deposition of coarser material leaving fines alone transported in the late stages of the storm as in Groups II to IV. Storms vary in the area they affect and in the speed with which they travel across the catchment (Colyer, 1981). Although these variations have not been monitored across this catchment it is likely that the more widespread storms will cover a greater area of the catchment and thus introduce sediment in larger quantities and from a greater variety of land uses.

Surface material consists mainly of individual, relatively fine particles which begin aggregation, cemented by precipitated silica, in slow-flowing or stationary surface water. Aggregates form rapidly in the drain however where silica precipitation and solution and abrasion considerably alter the sediment, as is shown in Chapter 7. Of the sediment collected during storms at the outfall, 44% formed bimodal size distributions representing largely, fine individual particles and coarser, aggregated sediment; 39% formed unimodal distributions and the remainder contained a mixture of the two. The majority of unimodal size distributions occurred in storms of Group I whereas the majority of bimodal distributions occurred in storms of Group II to IV. It is the purpose of this section to describe the sediment form and the changing patterns of the different types of distributions observed during storms in relation to hydrological and antecedent influences.

5.5.2. Unimodal Storms.

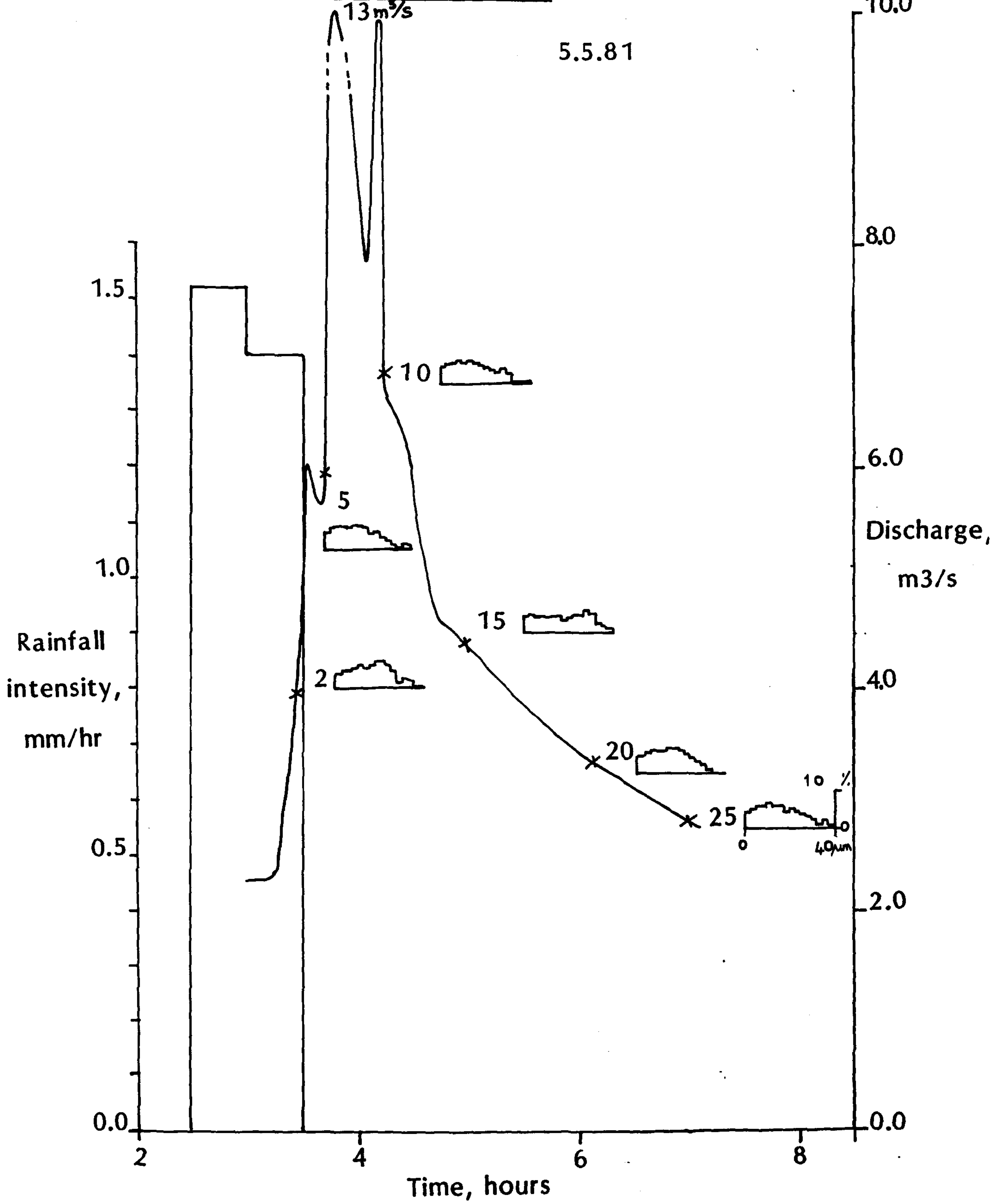
Almost all the unimodal sediment size distributions sampled occur in storms of Group I. This is significant because the storms of Group I are the most distinctive storms monitored as a result of their initial high intensity rainfall. The rainfall is of short duration (0.2 to 2.5 hours) but the high intensity (average approximately 2.5mm/hr) ensures that the sediment available on the surface and in the drain is rapidly collected in runoff over a short period and transported to the outfall. The sediment load thus includes a variety of sediment sizes and forms and remains similar throughout the relatively short period of discharge (2 to 2.7 hours). An example of sediment size variation is given in the context of typical Group I storm parameters in Figure 5.6.

The sediment sizes predominantly range from 1 to 40µm with a broad spread and high standard deviation values (4 to 10) and a slight to moderate negative skewness (1 to 3). Mean size values are 5 to 10µm and account for the majority of values in the distribution. However modal values occur between 4µm and 10µm and are more widely adopted in the analyses of changes through storms; the shifts in the modal size best describe the changing dominance of relatively fine and coarse sediment during the storms.

As mentioned above the high intensity rainfall collects all the sediment at once and thus the load contains a variety of mixed-size individual particles from the surface and any aggregated drain deposits from the previous storm. The load therefore at first contains a broad spread of particle sizes but there is a slight tendency for fines to predominate towards the end of the storm as the discharge decreases, as for example in the storm of 16.11.81 (Figure 5.7). Occasionally, a final increase of coarse sediment suggests aggregation is beginning (storm 14.9.81) but this is very limited in Group I storms. More commonly the discharge is sufficient to clear the drain of sediment before falling off rapidly (Figure 5.7). Within this overall pattern there are shifts in the modal size during

FIGURE 5.6

PARTICLE SIZE AND HYDROLOGY OF A TYPICAL STORM OF GROUP I.



the storm; the storms of 5.5.81 and 16.11.81 remain similar throughout; during the storm of 14.9.81 there is a shift in sediment sizes towards fines mid-storm either because the sediment becomes exhausted or because there is renewed input of fine individual particles. Then when fine sediment is just beginning to become aggregated the dominant size curves show coarser sediment. The storm of 14.9.81 is particularly interesting because the preceding storm was only 55 hours before and will have left the system clear but, as coarse material is sampled early in the storm, the initial rainfall intensity must have had a particularly severe effect to have collected and transported such material through the system. In this case the coarse sediment probably comprises individual particles as there is no evidence of aggregation taking place. In the storm of 14.9.81 there is probably some renewed input of fine sediment mid-storm, as mentioned above, which is caused by a high secondary discharge peak (Figure 5.6A). The effects of renewed sediment input are seen in Group I storms where major secondary discharge peaks are not uncommon whereas the more minor fluctuations of other storm groups have no noticeable effect on the sediment. The relative abundance of fine material in the storm of 14.9.81 may be responsible for encouraging aggregation which is otherwise rare in this storm group. The storm of 18.9.81 was of exceptionally high rainfall intensity which maintained a broad spread sediment distribution throughout the storm until the sediment was cleared and a few remaining fines became aggregated in the prolonged falling discharge. The storms of 1.6.81 and 7.10.80 show irregular shifts in modal sediment size which cannot easily be explained except perhaps by the low availability of sediment in each case.

An attempt was made to elucidate the influences on modality of the antecedent conditions and storm characteristics (Figure 5.8A). Despite the variations in sediment sizes during the storms some trends emerge and the divergences in different storms can be explained. The modality was measured as the average percentage of coarse particles of the size distributions for each storm. The unimodal storms therefore fall along the line of 100% while the remainder are bimodal or of mixed modality. Positive

FIGURE 5.6A.

PARTICLE SIZE AND HYDROLOGY OF GROUP I STORM, 14.9.81.

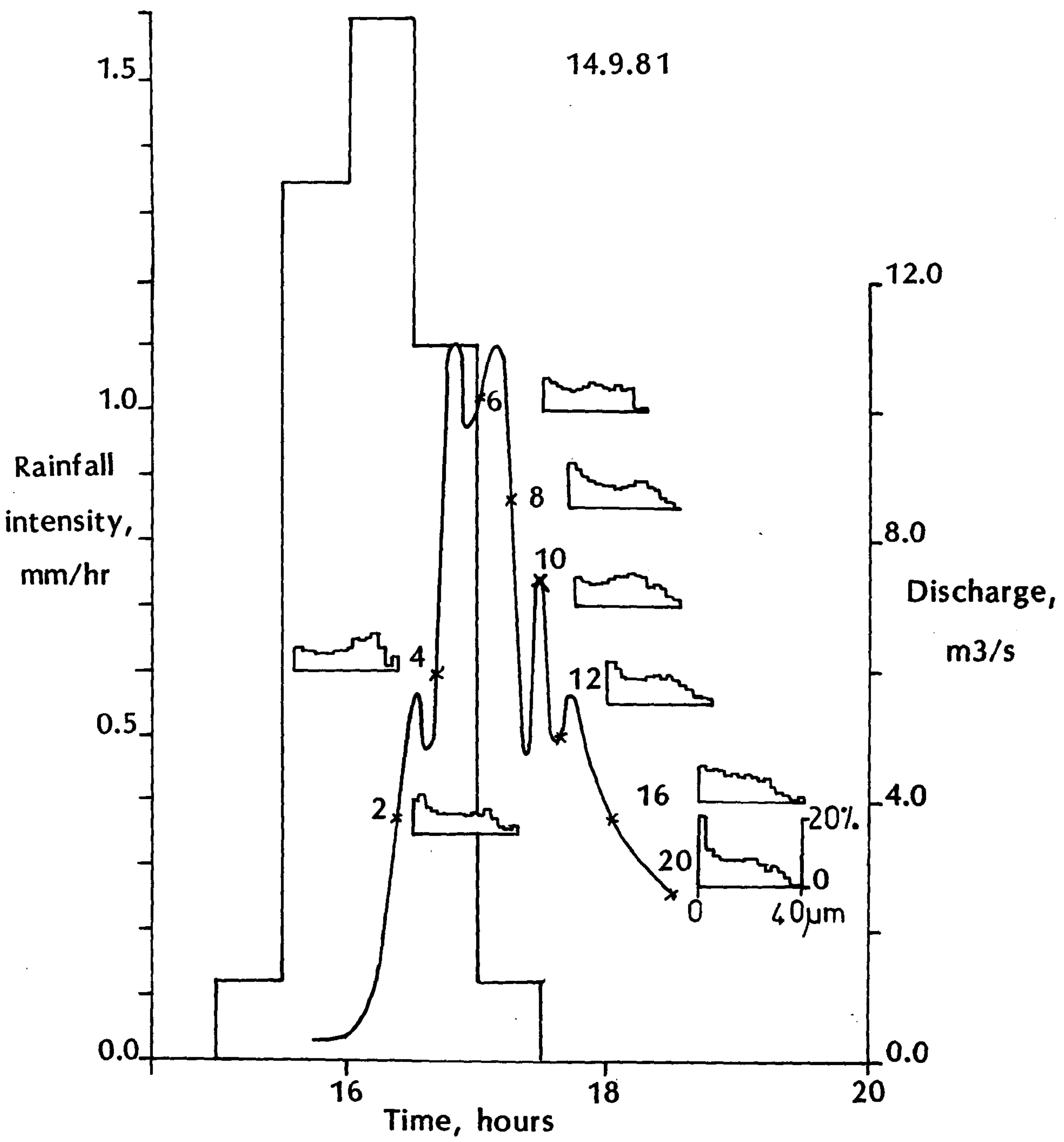


FIGURE 5.7.

PARTICLE SIZE DISTRIBUTIONS OF GROUP I STORMS.

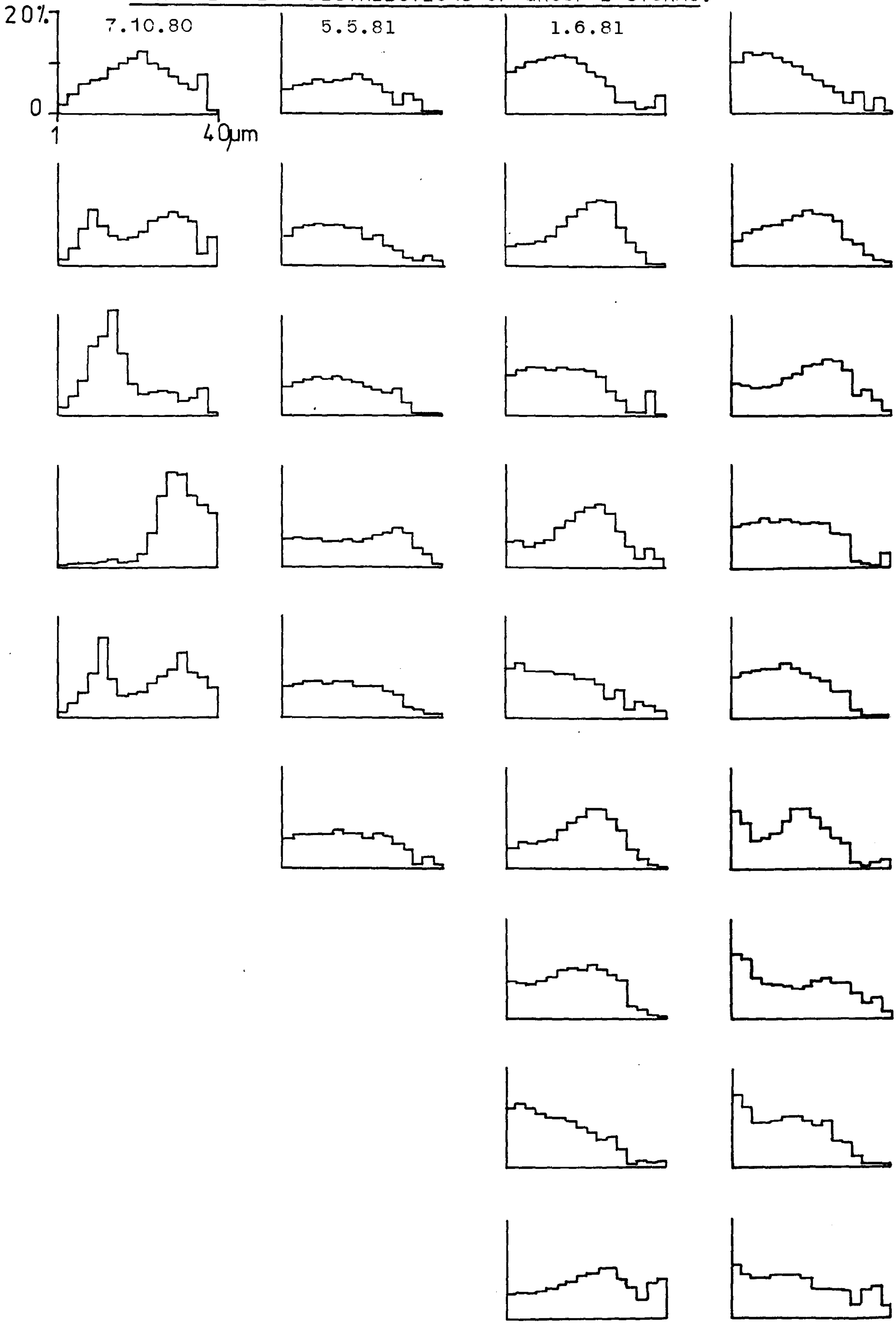


FIGURE 5.7. (continued)

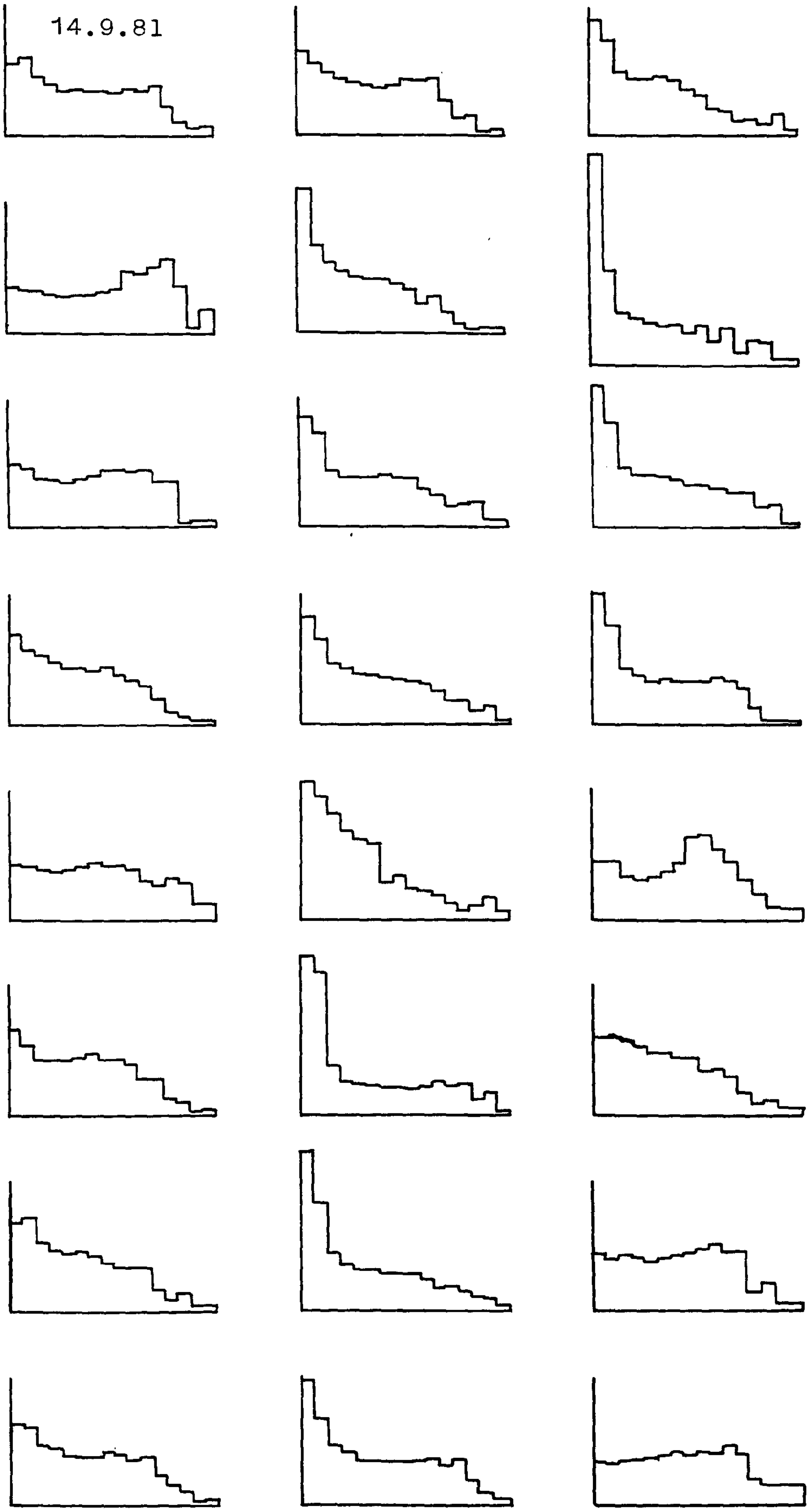


FIGURE 5.7. (continued)

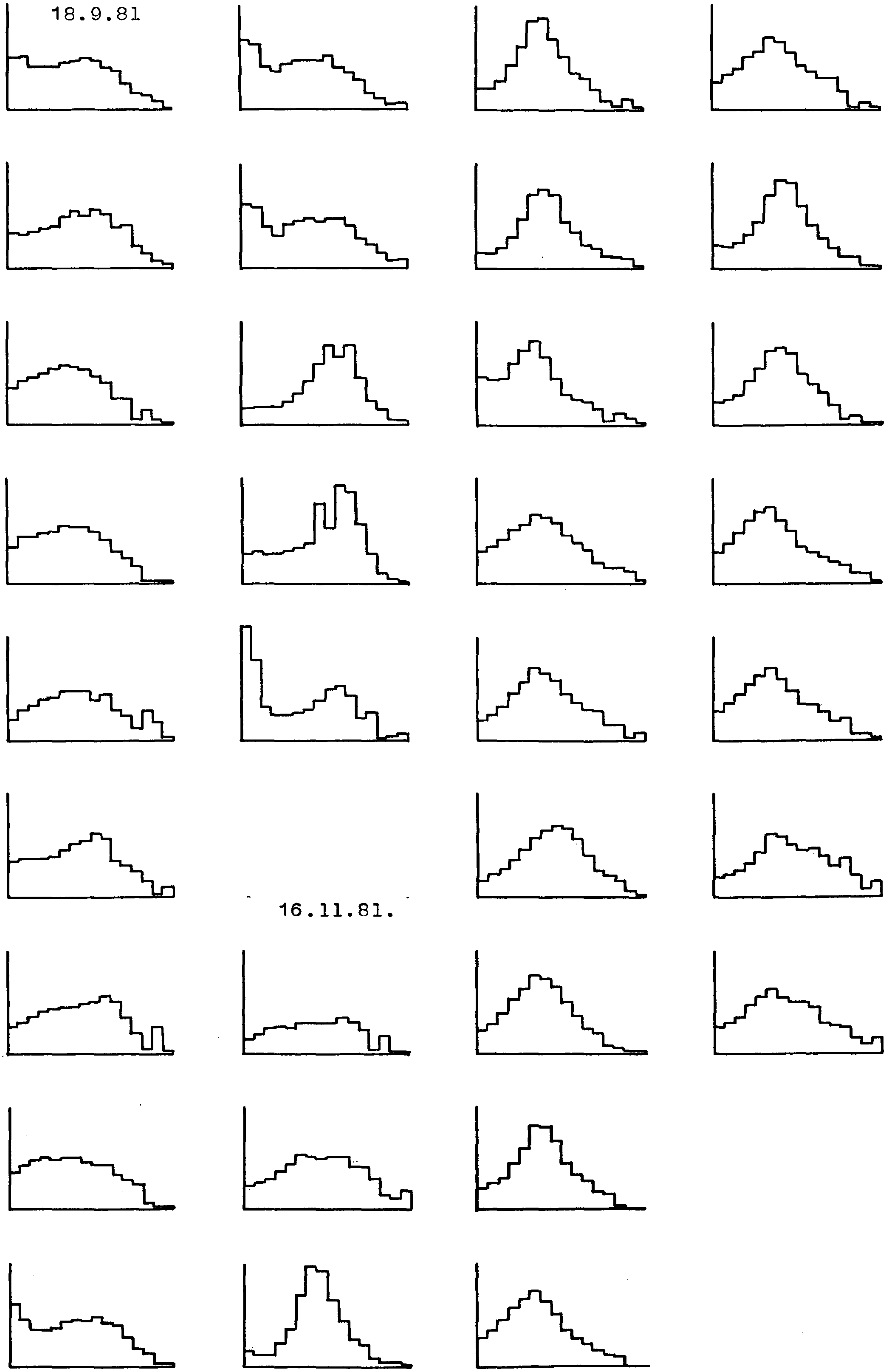
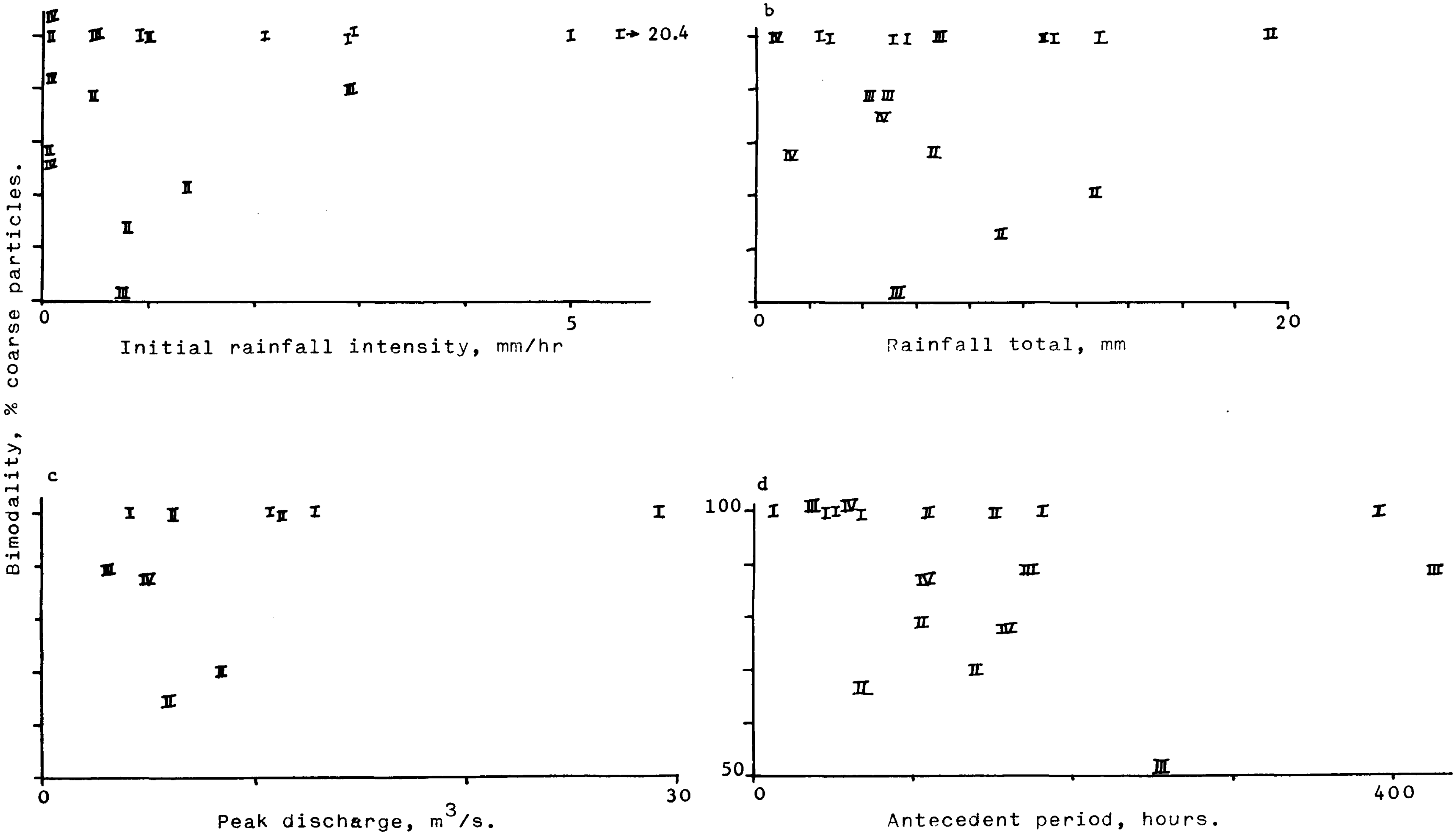


FIGURE 5.8A.

RELATIONSHIP BETWEEN SIZE MODALITY AND STORM GROUP CHARACTERISTICS.



influences on modality can be seen from all four parameters. Where unimodal storm distributions appear to oppose this trend (Figure 5.8Ab and d) the high initial rainfall intensities of Group I storms have the overriding influence. Some Group IV storms are slightly different in that their low discharge transports very little sediment in at irregular intervals and no clear trends emerge.

There is a minority of storms from Groups II to IV which have unimodal size distributions as opposed to the bimodal ones which are more usual for those groups. The Group II storm of 3.5.81a (Figure 5.9) is of unimodal size distributions and is quickly followed by the Group III storm of 3.5.81b and the discharge does not regain base level between the two. This is unusual and the automatic sampler probably did not distinguish between the two storms but this does not seem to help explain the unimodal distributions. The Group III storm of 30.3.81 (Figure 5.11) is anomalous in a number of respects; although the antecedent dry period was short (42 hours) and the rainfall only average about half of the samples exceed 40μm and some contain sediment up to 88μm. Although this larger sediment occurs in very small quantities it does alter the size range and may affect the distribution. The reason for the tendency towards unimodality in the largely bimodal Group III storm of the 10.9.81 (Figure 5.10, 5.11) is easier to explain. There is a high sediment availability both from previous drain deposits and an exceptionally long antecedent dry period of 505 hours. Thus an abundance of sediment of all sizes is readily available for entrainment. The unimodality of the Group IV storm of 17.3.81 (Figure 5.13) may be explained by the low flow conditions favouring aggregation with the result that the distribution describes an approximately normal curve for aggregates. This is borne out by the appearance of fine particles only in the first sample after which it is most probable that they were incorporated into aggregates.

5.5.3. Bimodal Size Distributions.

The bimodal sediment size distributions were the most common form of the size curves measured in this study. The bimodal distributions occurred in the storms of Groups II, III and IV and are explained here largely in terms of the antecedent conditions and discharges of those storms (Figures 5.83, 5.10, 5.12, Table 5.3)

The sediment covers the size range of 1 to 40μm with between 20% and 50% falling in the finer range of 1 to 3μm (Figures 5.9, 5.11, 5.13). These portions of the total size distributions are usually normally distributed, with standard deviation values of 0.2 to 0.6 and low skewness values of 0 to 1, but tend to be leptokurtic (Kurtosis 1). The coarser fraction comprises 50 to 80% of the total size distributions and ranges from 3 to 40μm. The majority of curves are negatively skewed (1 to 3) and platykurtic.

In every sample of each storm the modal size of 2 to 3μm and the upper size limit of 3μm of the fine curves remains remarkably constant. In the coarser fraction the modal sizes vary within the range 9 to 18μm and two or three shifts of modal size commonly occurred during each storm. The point of division between the two distributions is very consistently at 3μm through storms as mentioned above and deviates only rarely as for example in the storm of 10.9.81. This storm has already been described as tending towards unimodality as a result of the abundance of sediment available. Towards the middle of the storm the division was spread over the size range of 8 to 9μm.

The study shows that sediment collected at the outfall during storm sampling comprises individual relatively fine particles from surface accumulation and the aggregates which formed from them during drainflow. Aggregates deposited and developing at the cessation of previous stormflow are collected early in the

FIGURE 5.8B

PARTICLE SIZE AND HYDROLOGY OF GROUP II STORM, 6/7.10.80.

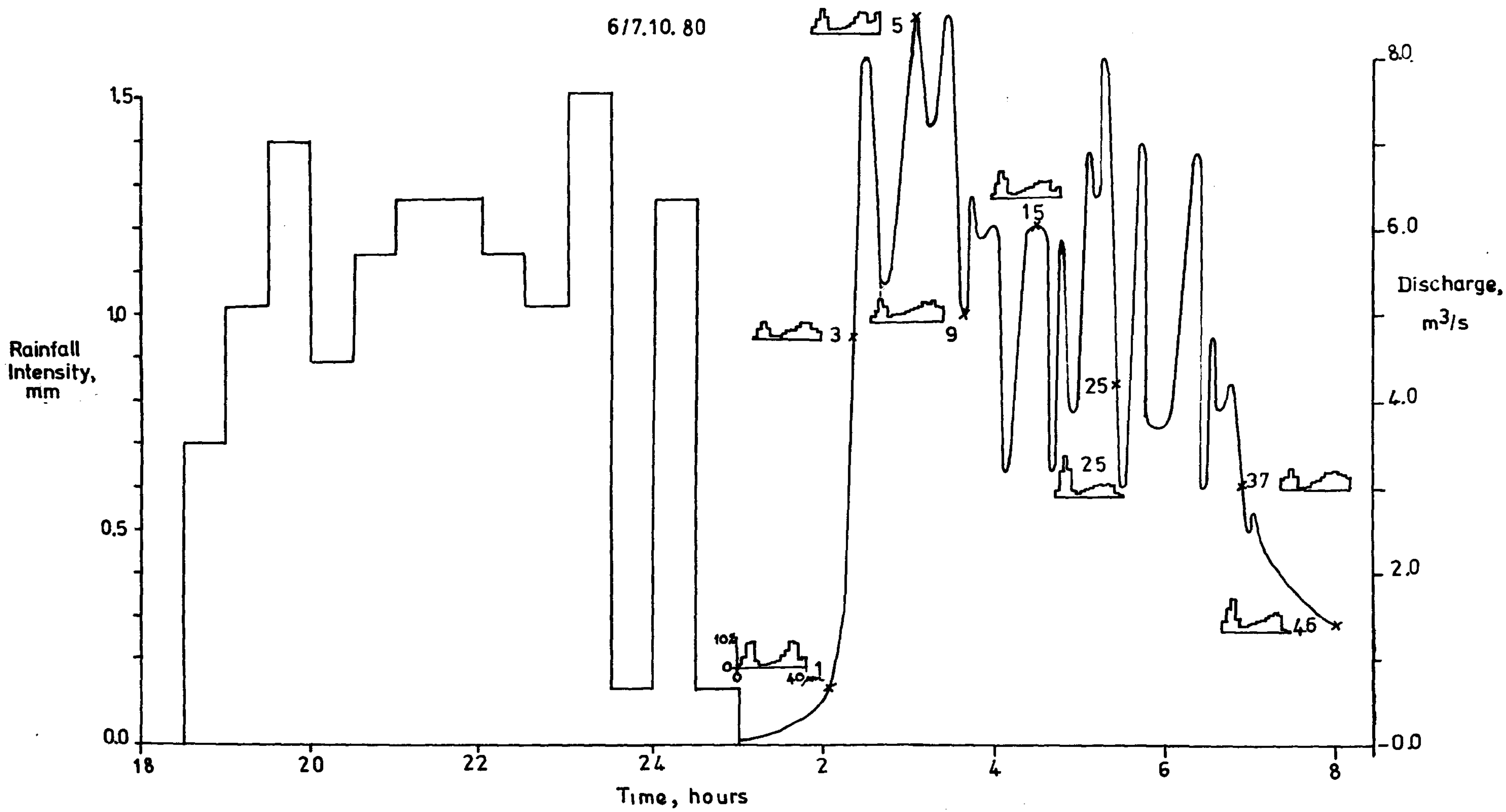


FIGURE 5.9.

PARTICLE SIZE DISTRIBUTIONS OF GROUP II STORMS.

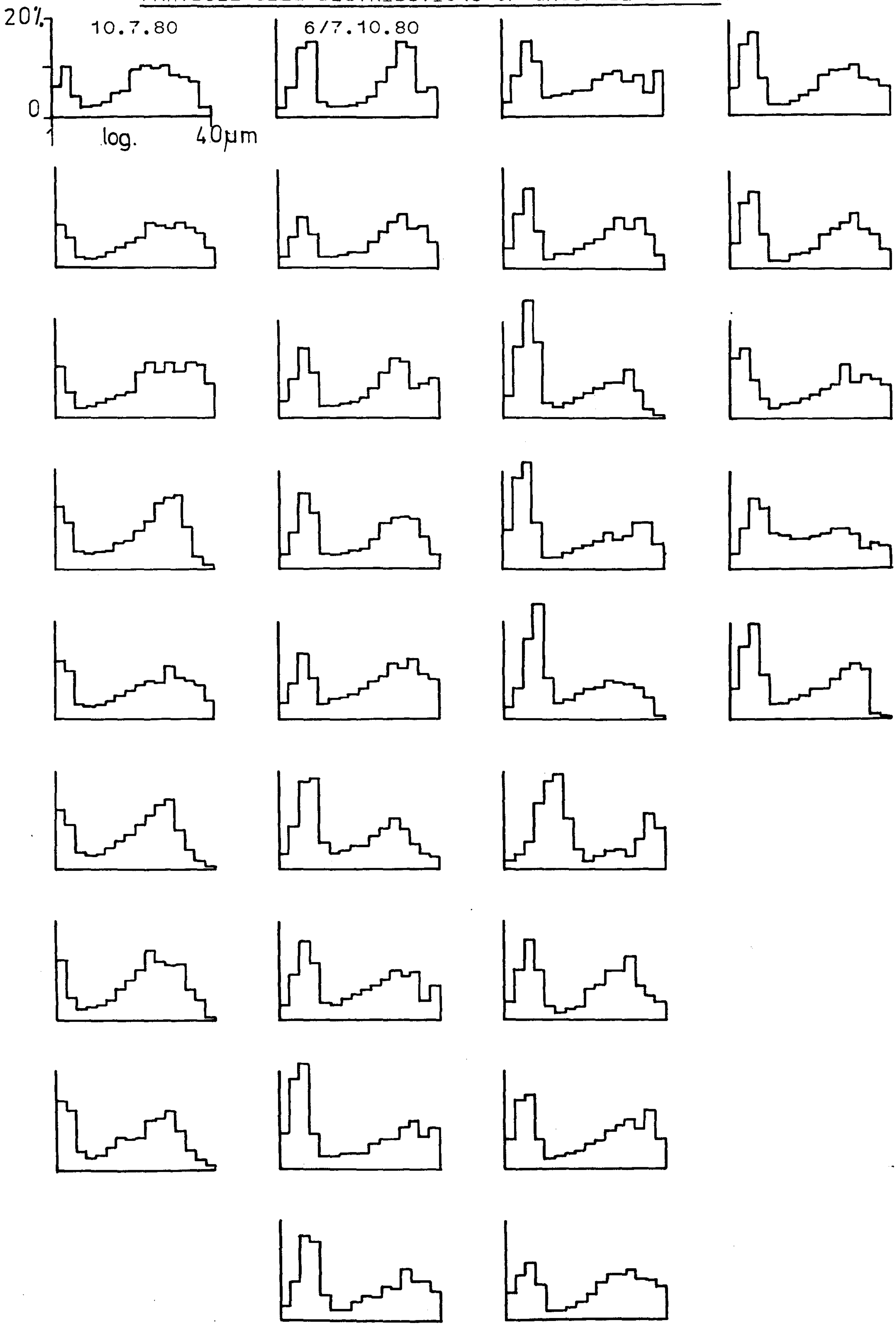


FIGURE 5.9. (continued)

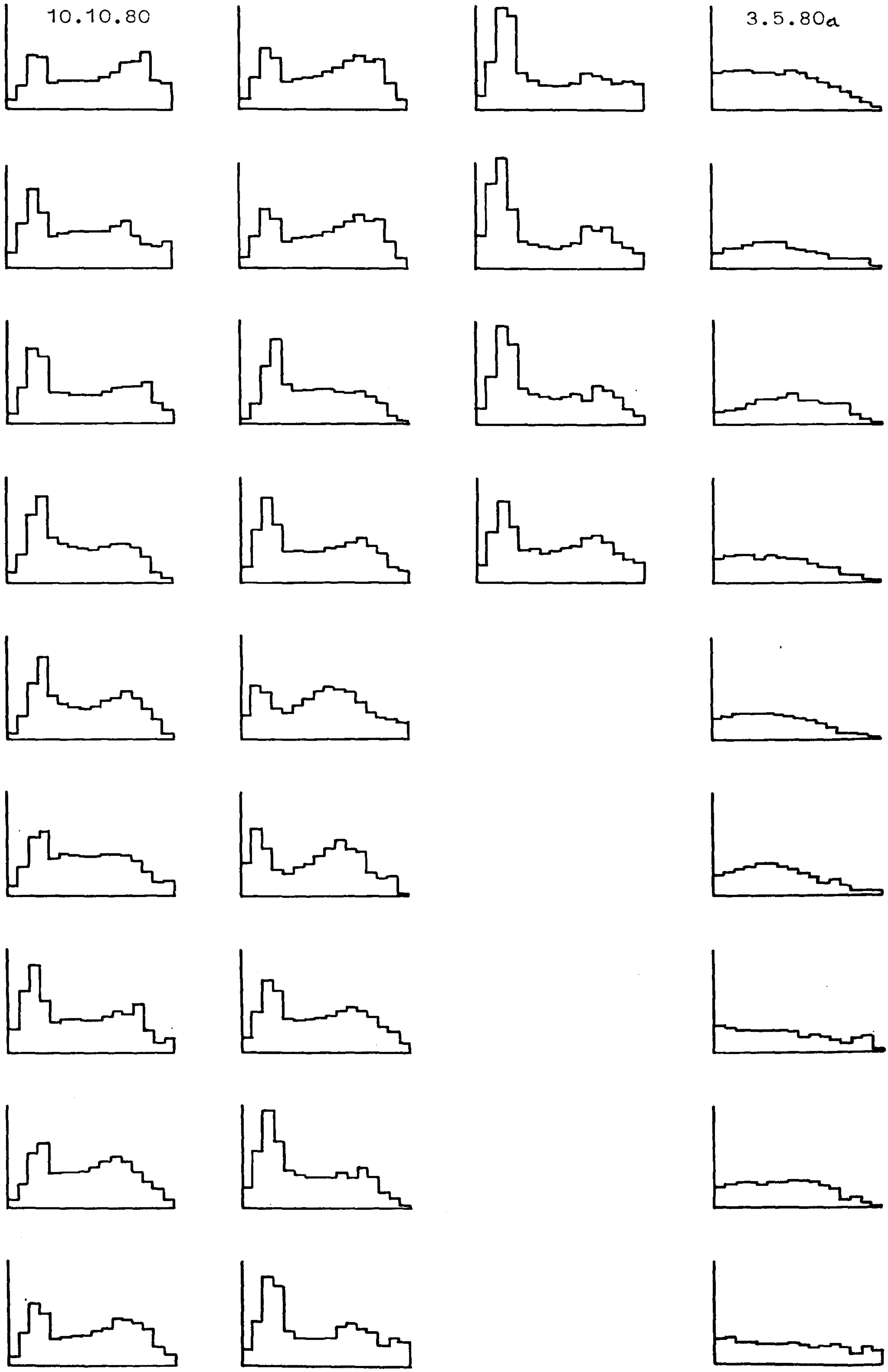
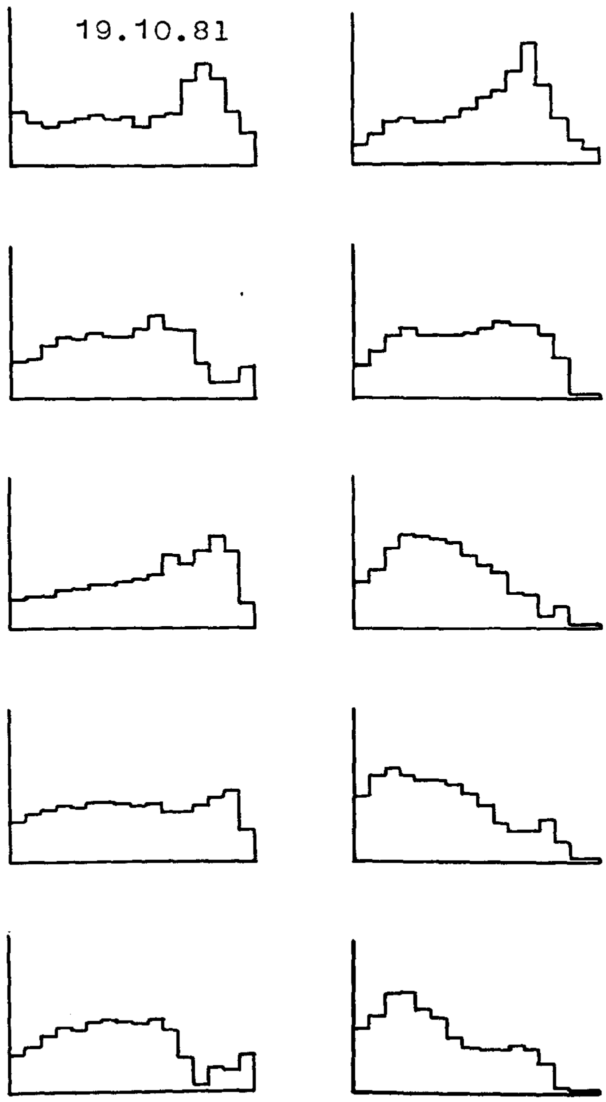


FIGURE 5.9. (continued)



subsequent discharge whereas those formed in current flow take until the middle or end of the storm to develop and reach the outfall. From the examination of the shifts in modal sizes and in the percentage variations between fine and coarse sediment the following conclusions were drawn. It can be seen that all storms where the early sediment load is dominated by fine particles (Figures 5.9, 5.11, 5.13) begin with low intensity rainfall (Table 3.4, Figures 5.8B, 5.10, 5.12). The stormflow only transports fine material until the discharge increases sufficiently to transport coarser sediment. In the typical storms of 8/9.7.80 (Figure 5.12) 10.7.80 and 6/7.10.80, (Figure 5.8B) for example, coarser sediment was readily available for entrainment since they were all preceded by other storms which would have deposited material during the final falling discharge,and by a prolonged antecedent dry period (Table 5.3) during which surface sediment would have accumulated. The Group IV storms are usually slightly different as for example the storm of 26.11.81 which followed the deposition of a little fine material in the system and a prolonged accumulation period. In this case, although coarser sediment was available, the low discharge could not transport it and only fine particles were carried until the middle of the storm. The discharge rarely reached a sufficient level to transport coarser material any great distance and the distributions late in the storm describe aggregates formed from the fine particles during the slow flow.

The early stages of a few of the storms of bimodal size distributions tend to be dominated by relatively coarse sediment as for example in the storm of 14.11.80 (Figure 5.11). These particles are usually aggregates which were formed and deposited by the previous storm. The early discharge is sufficient to entrain these drain aggregates at least by the time the flow nears the outfall, and to transport them to the sampling point.

The later stages of the bimodal size storms of Groups II to IV are characterised by a gradual decrease in discharge and thus

FIGURE 5.10

PARTICLE SIZE AND HYDROLOGY OF GROUP III STORMS, 10.9.81.

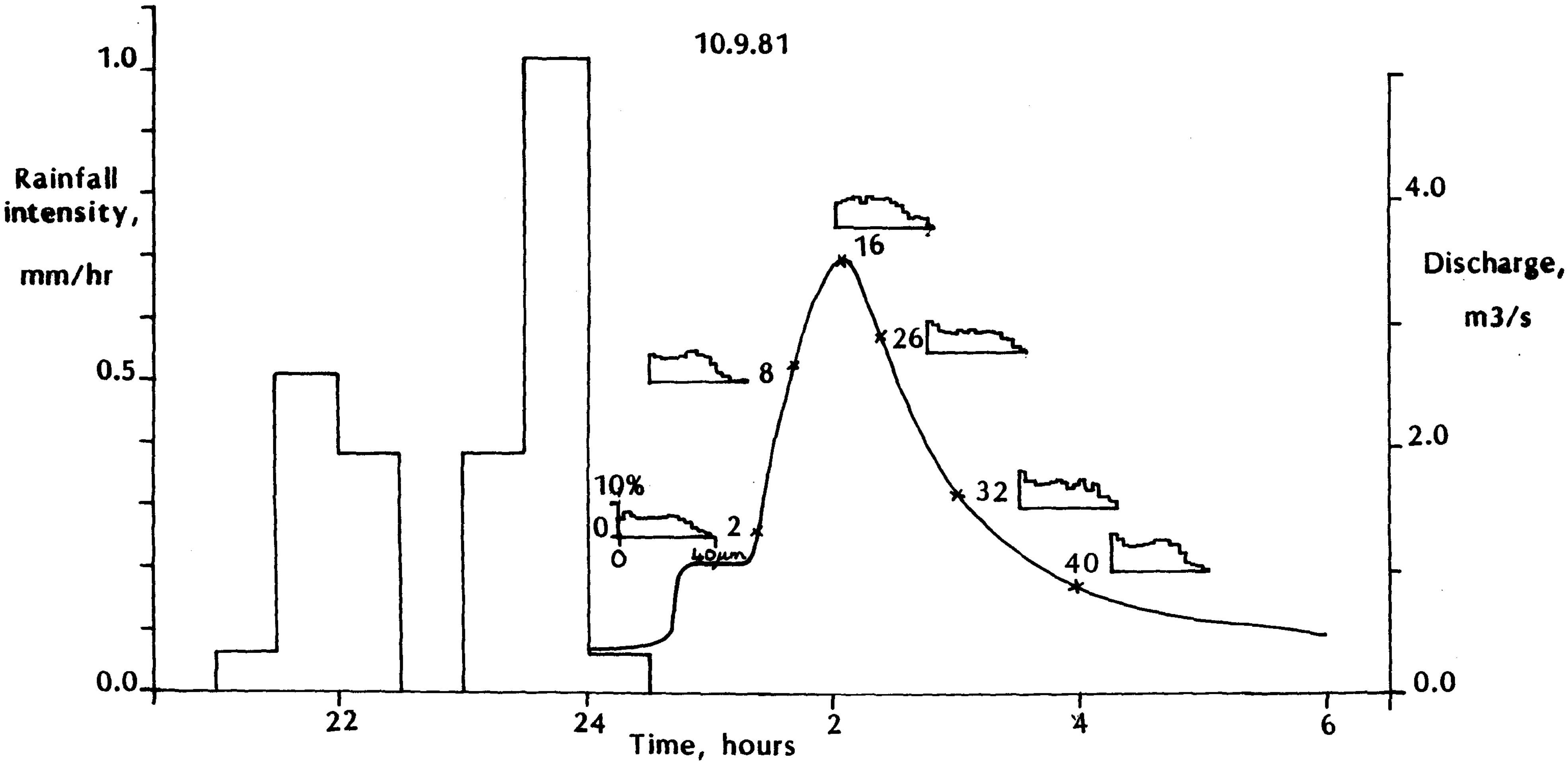


FIGURE 5.11

PARTICLE SIZE DISTRIBUTIONS OF GROUP III STORMS.

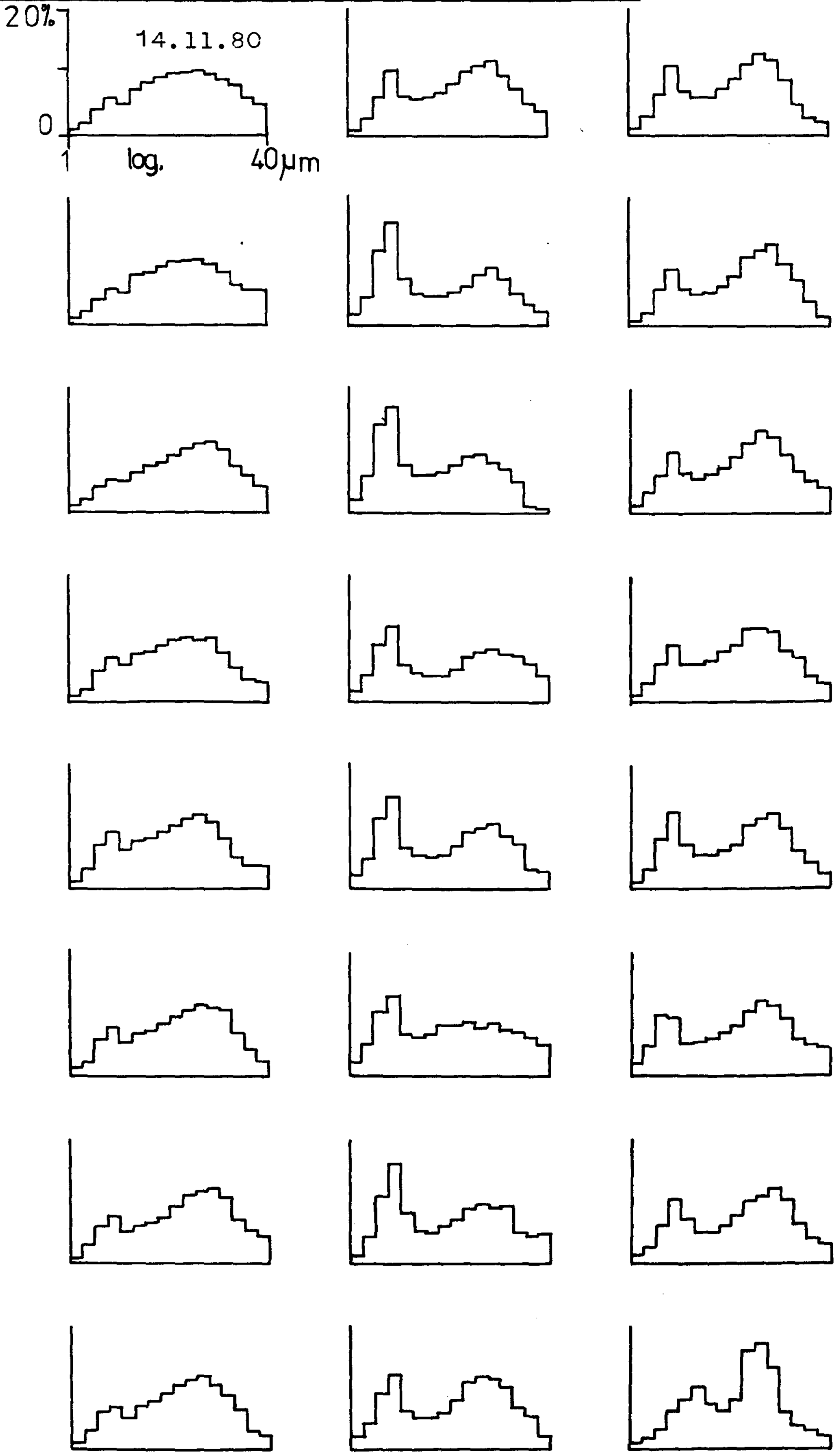


FIGURE 5.11 (continued)

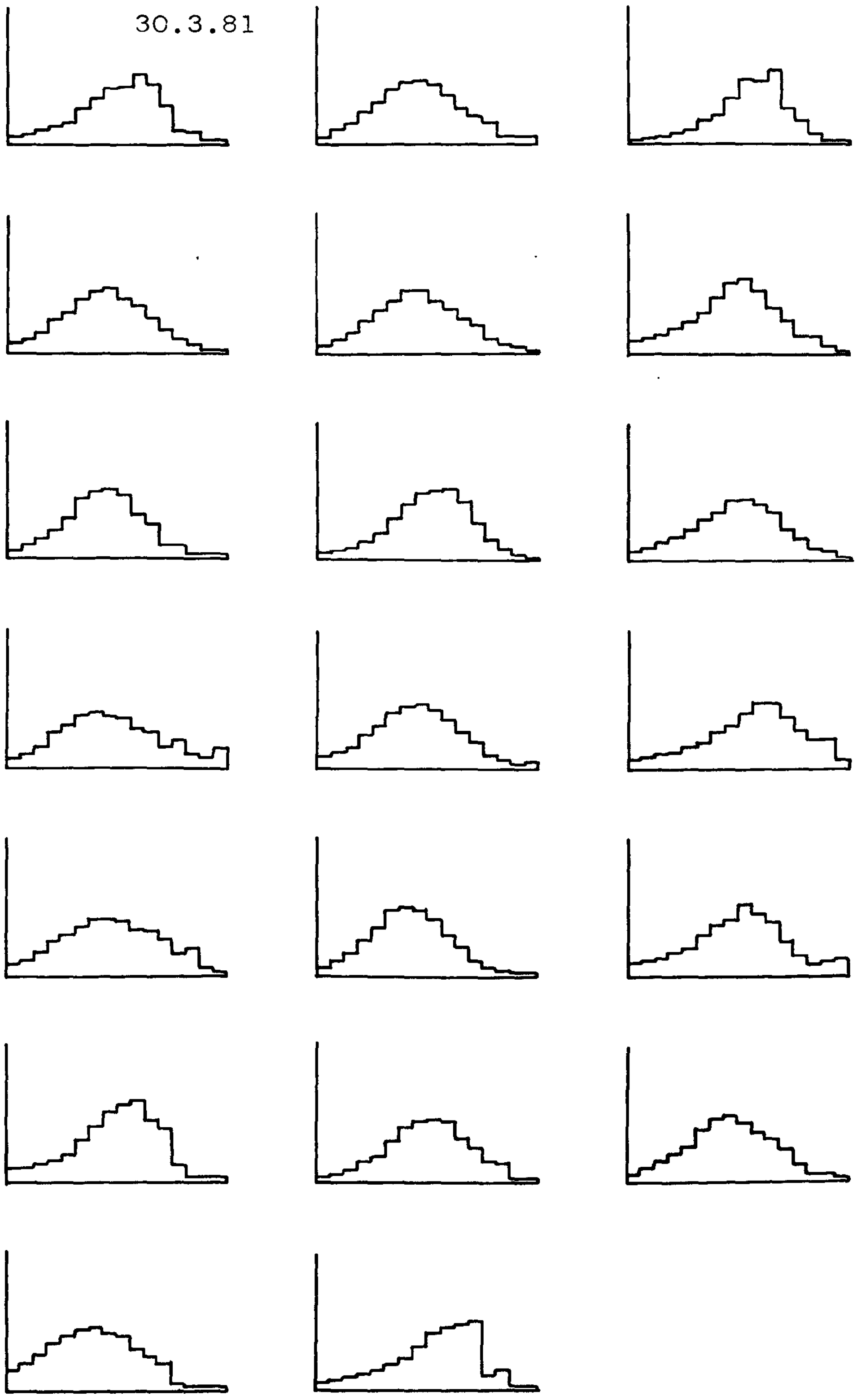


FIGURE 5.11. (continued)

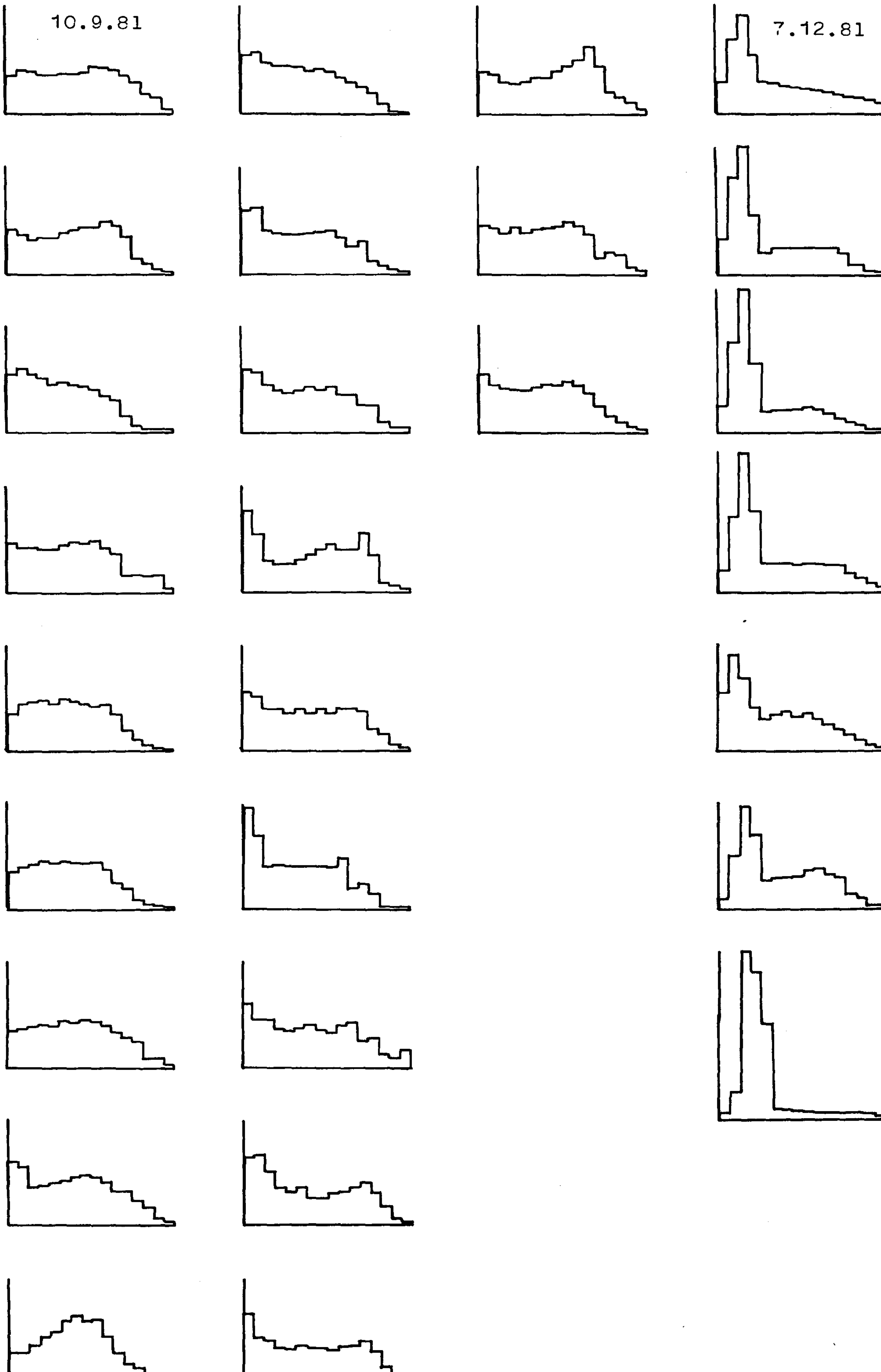


FIGURE 5.12.

PARTICLE SIZE AND HYDROLOGY OF A TYPICAL GROUP IV STORM.

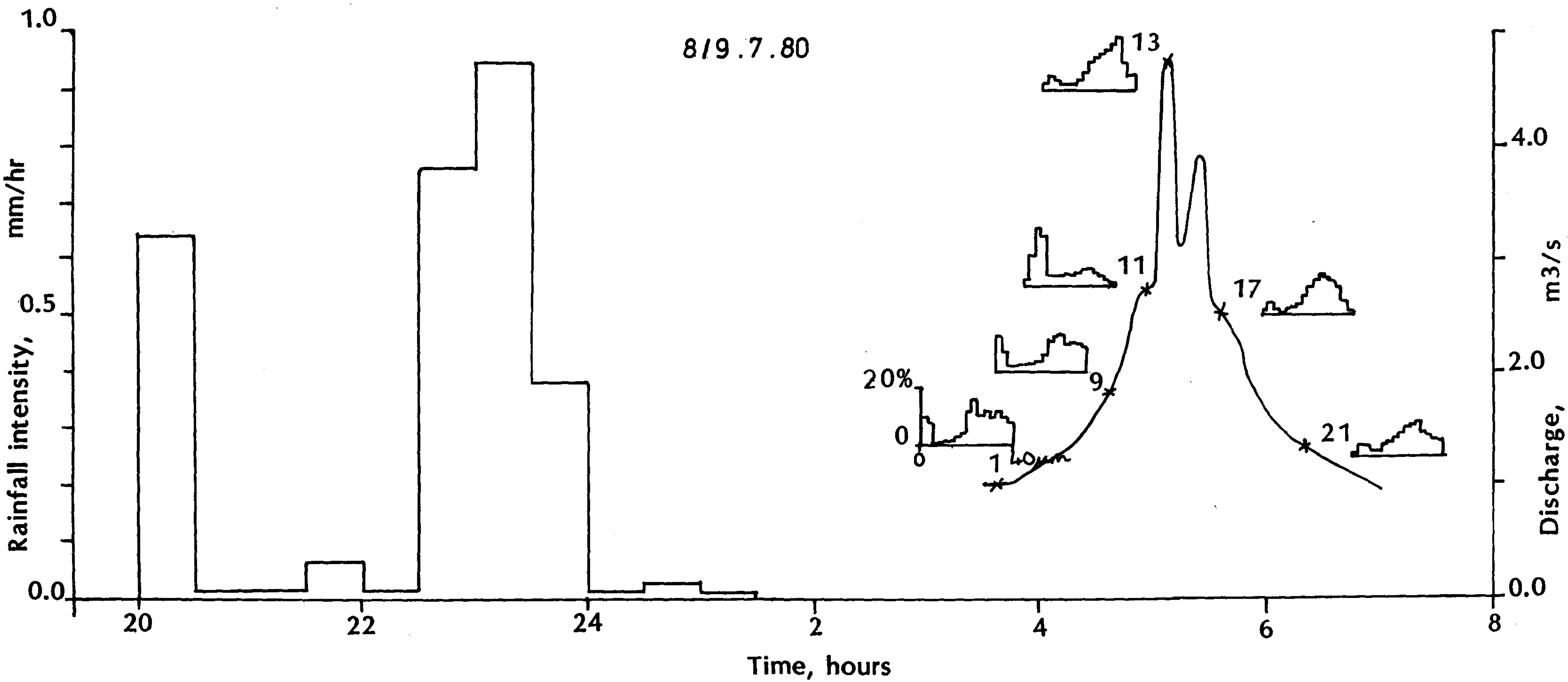


FIGURE 5.13

PARTICLE SIZE DISTRIBUTIONS OF GROUP IV STORMS.

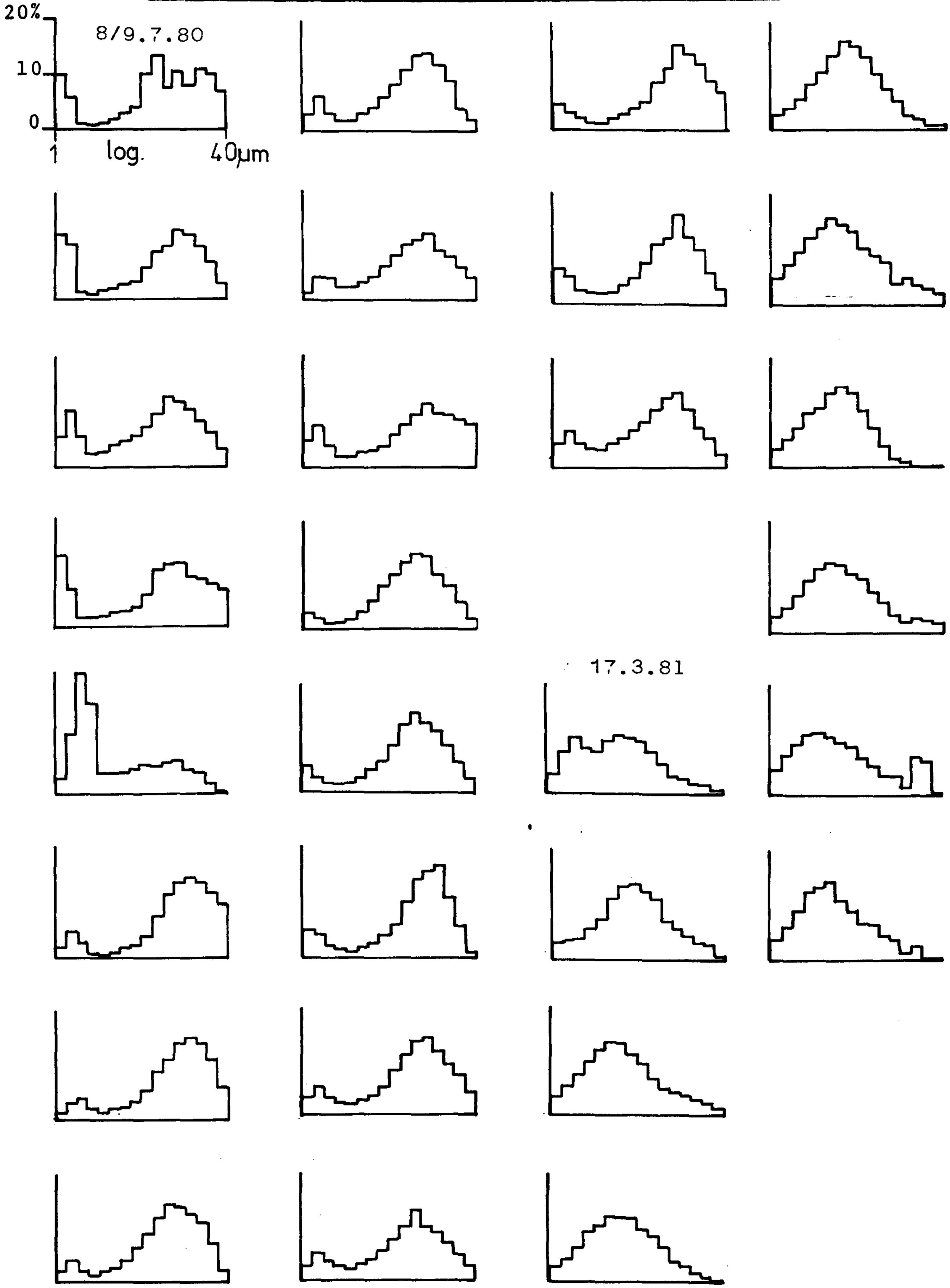
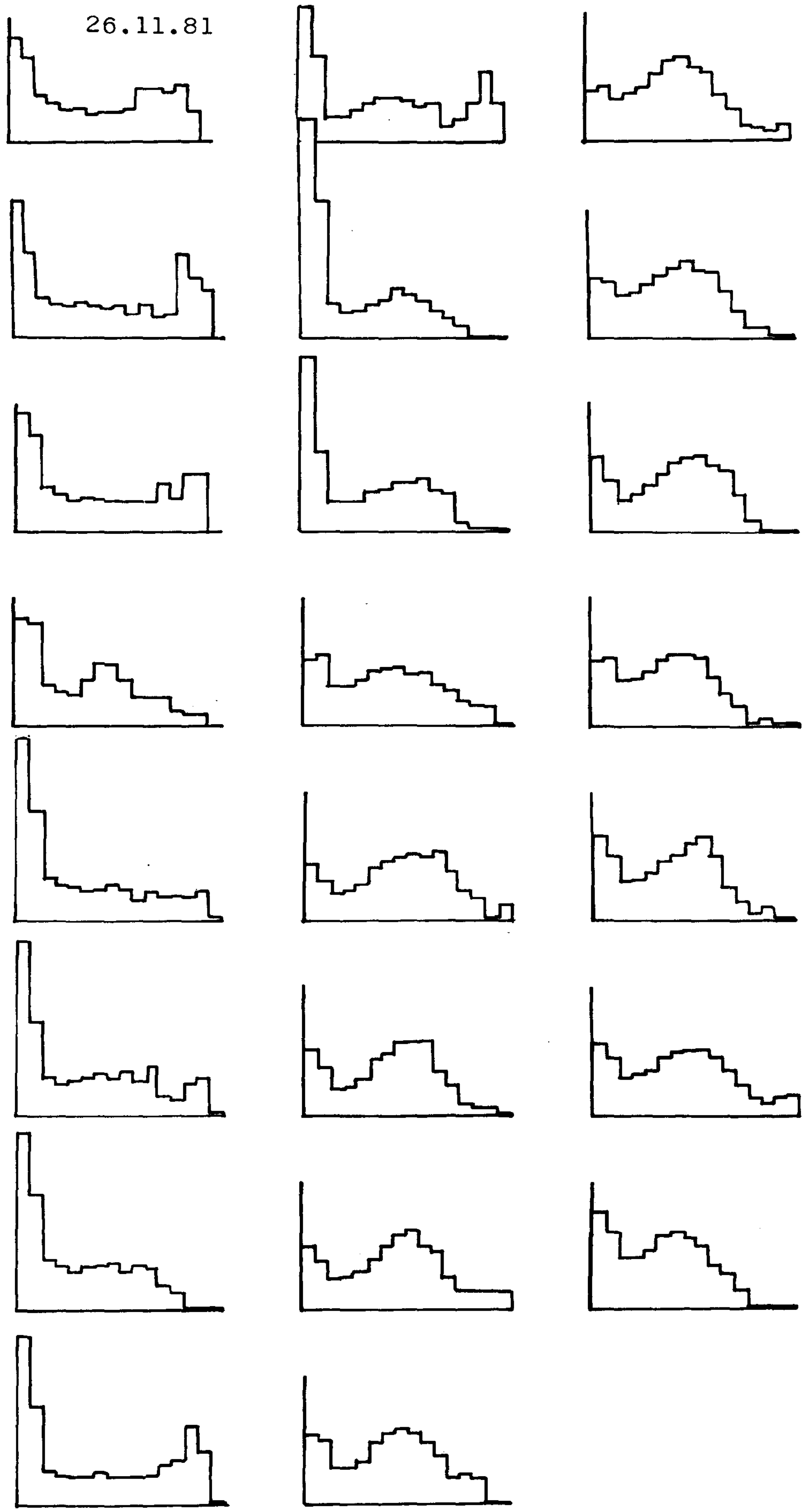


FIGURE 5.13. (continued)



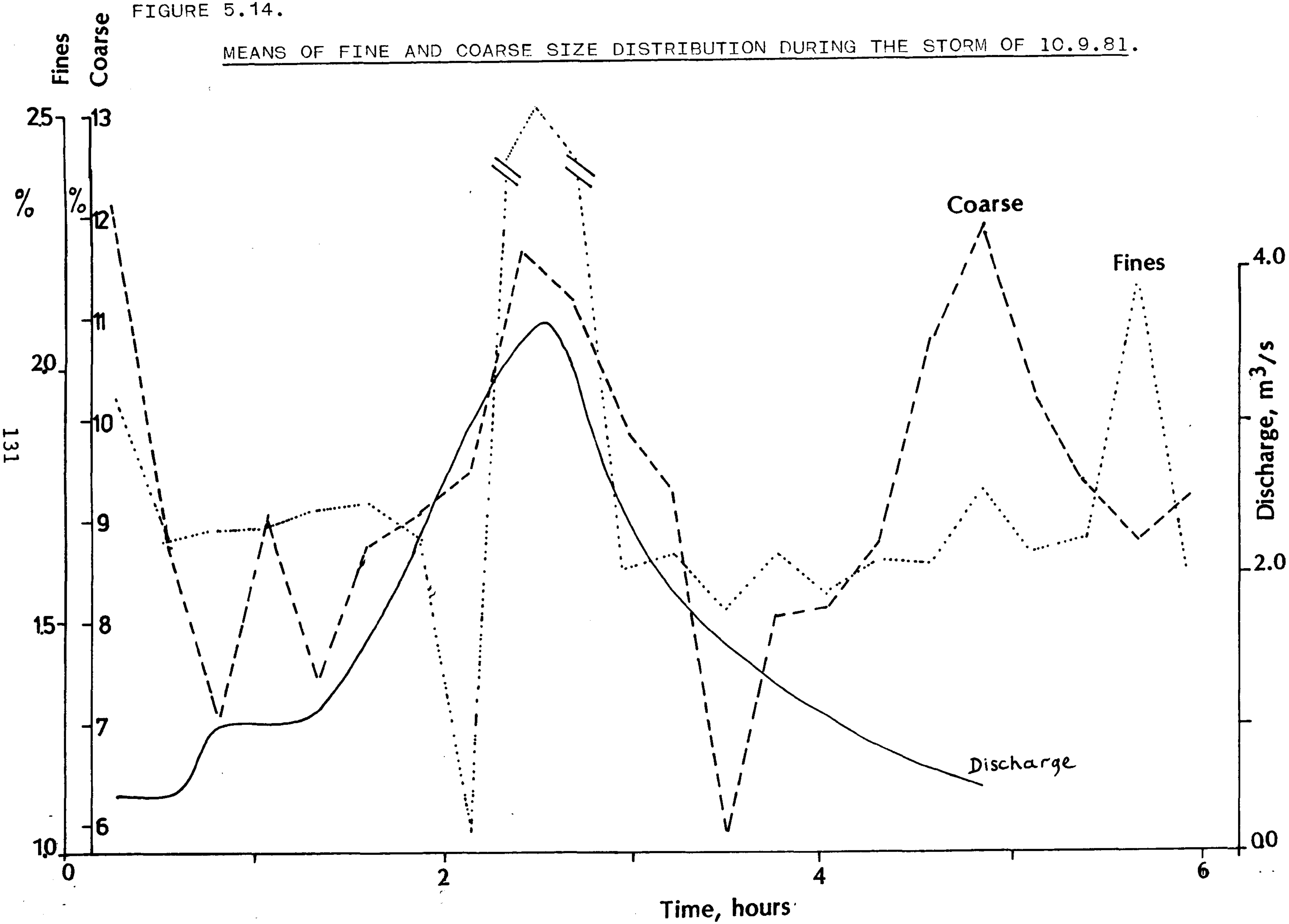
only fine material can be carried at the end of the storm. In addition, some of the Group II storms could well have been of high enough discharge for sufficient duration to have cleared the system of coarser material. Occasionally however coarse sediment appears to predominate at the end of the storm, as for example in the storm of 10.10.80. This sediment comprises aggregates, formed during the late stages of the storm, but as they are deposited in the falling discharge their presence indicates the continued flow of the discharge beyond the time range of the sampler. The true final stages of the storm will be dominated as described above by low capacity and fine particles.

Taking the storm of 10.9.81 as an example (Figure 5.14) a plot of the means of the fine and coarse distributions through the storm shows clearly the early dominance of fines with the initial low discharge; the increase in coarse material with discharge; an abundance of sediment with peak discharge; and a late increase in coarse material with aggregation, followed by the returning dominance of fines as the discharge falls.

Bimodal distributions were the most common form of size curve measured in the study catchment and the question arises whether bimodal distributions occur in other types of drainage system or whether they are specific to this catchment. From a study of the literature it appears that almost no sediment within a transport system can be regarded as pure in composition or in grain size. Water and wind movement mixes sediments, deposits some fractions and moves others. Bimodal distributions are rarely reported but data are available on polymodal sediment size distributions. Study areas are limited a fact which itself reduces the number of sediment modes sampled. In most cases the bimodal distributions appear to be the result of a study confined to two sediment sources or to two transport mechanisms. In the main, sediment size modes are considered to be related to transport mechanisms,

FIGURE 5.14.

MEANS OF FINE AND COARSE SIZE DISTRIBUTION DURING THE STORM OF 10.9.81.



most commonly the differences studied are due to suspension, saltation and traction (Folk and Ward, 1957; Fuller, 1961; Visher, 1969; Binda and Hildred, 1973; Middleton 1976; Sagoe and Visher, 1977; Ashley, 1978; Walton, Stephens and Shawa,1980). The origin of the sediment however is considered largely to determine its absolute size (Mason and Folk, 1958; Spencer, 1963; Hollister and Heezen, 1964)

Most of the stormwater sediment studied is from the suspended fraction and the two size modes represent individual and aggregated particles respectively. If traction and saltation loads were also sampled then the bimodality of the suspended sediment size distribution would be a subsection of the poly-modal size curve of the entire load. Inevitably some mixing occurs between the sediment fractions sampled due to the turbulence of the flow and the fixed position of the sampler intake near the bed. However, the small size of the intake nozzle largely restricts the sediment size sampled to the finer, predominantly suspended fraction of less than 40µm. The particle size of the sediment sampled was not merely a function of the nozzle aperture; the dominance of suspended sediment at the depth of the nozzle was demonstrated by hand sampling with an unrestricted, wide-necked container.

From the literature it can be seen that the origin of the sediments is a major influence if they are of substantially different size ranges and are present in comparable quantities. However, when this is the case, transport mechanisms are the more frequent differentiators of size with the energy levels sorting the sediment.

5.5.4. Sediment Size Distributions of Mixed Modality.

During a minority of storms the size distrubutions are of mixed modality. The size curves vary between unimodal and bimodal during the course of the storm and are considerably more varied in both form and sequence than those from either wholly unimodal or wholly bimodal distributions. Considerable, often irregular, modal size fluctuations occur between successive samples which cannot always be easily explained in terms of rainfall intensity, discharge or antecedent conditions.

The storm of the 7.10.80 was short (1.5 hours) and generated only six samples, all of contrasting size distributions. As the accumulation period was only 11 hours and the drain had previously been left clear of sediment very little sediment was available. Initially sediment of all sizes was collected from the surface forming a unimodal distribution. The second sample was distinctly bimodal although there is no evidence of aggregates being secreted in the drain: as sediment was removed the peak discharge was dominated by fines but a secondary surge in rainfall intensity and discharge renewed the dominance of coarse particles in Sample 4. Finally, aggregation contributed to a bimodal distribution in the falling discharge. Although this is a plausible explanation from the evidence available the pattern of change is more extreme and occurred more rapidly than has been seen previously and may have been accentuated by the lack of sediment and high intensity of the rainfall creating irregular fluctuations in discharge.

That the hydrological conditions are mainly responsible for some irregularities in sediment size distribution is borne out by the presence of the two extreme storms in this mixed modality group. The storm of 18.9.81 is of extremely high initial rainfall intensity (20.4mm/hr) and although it was of short duration (15 minutes) substantial discharge was generated which lasted for 5 hours. The high initial intensity and high discharge generated unimodal size distributions but these were succeeded by bimodal curves in the late stages of the falling discharge when aggregation could take place. The storm of 19.10.81 was of extremely high total rainfall and unfortunately the exceptionally large volume of discharge severed the intake nozzle. The samples obtained until then from the rising discharge were like those of other Group II storms but it is considered that unimodal distributions would have followed with the unusually long rainfall duration and large scale sediment collection.

The storm of 17.11.81 is of mixed Grouping I/II and the size curves are of mixed modality. Further, this storm and other isolated samples possibly exhibit trimodality as in Samples 40, 42, 44, 47 and 48 (Figure 5.15 and 5.16) with modal size classes, for example, in Samples 40 and 42 at 1.2μm, 6μm and 15μm. The modal sizes are discernible but not well developed compared with bimodal curves and it is suggested that they represent individual fine particles, individual coarse particles and coarse aggregates respectively. The sizes are verified from particle measurements of photomicrographs but the number of particles available on them is too small for that evidence alone to be conclusive. However, taking into consideration the short antecedent dry period and the pattern of rainfall intensity the hypothesis is acceptable. Once more the strongly fluctuating discharge may well be responsible for the sediment size variations.

As has been mentioned, discharge fluctuations in storms of Groups II to IV usually have little effect on particle size whereas those of Group I storms go some way to explain variations in size. In the four storms described here the rainfall generated discharge surges which are more deeply divided than in any other storm and which appear to coincide with outstanding irregularities in sediment size distributions. Although the system is clearly very complex this explanation appears to help considerably in understanding at least the larger scale size variations.

FIGURE 5.15

PARTICLE SIZE AND HYDROLOGY OF THE STORM OF 17.11.81.

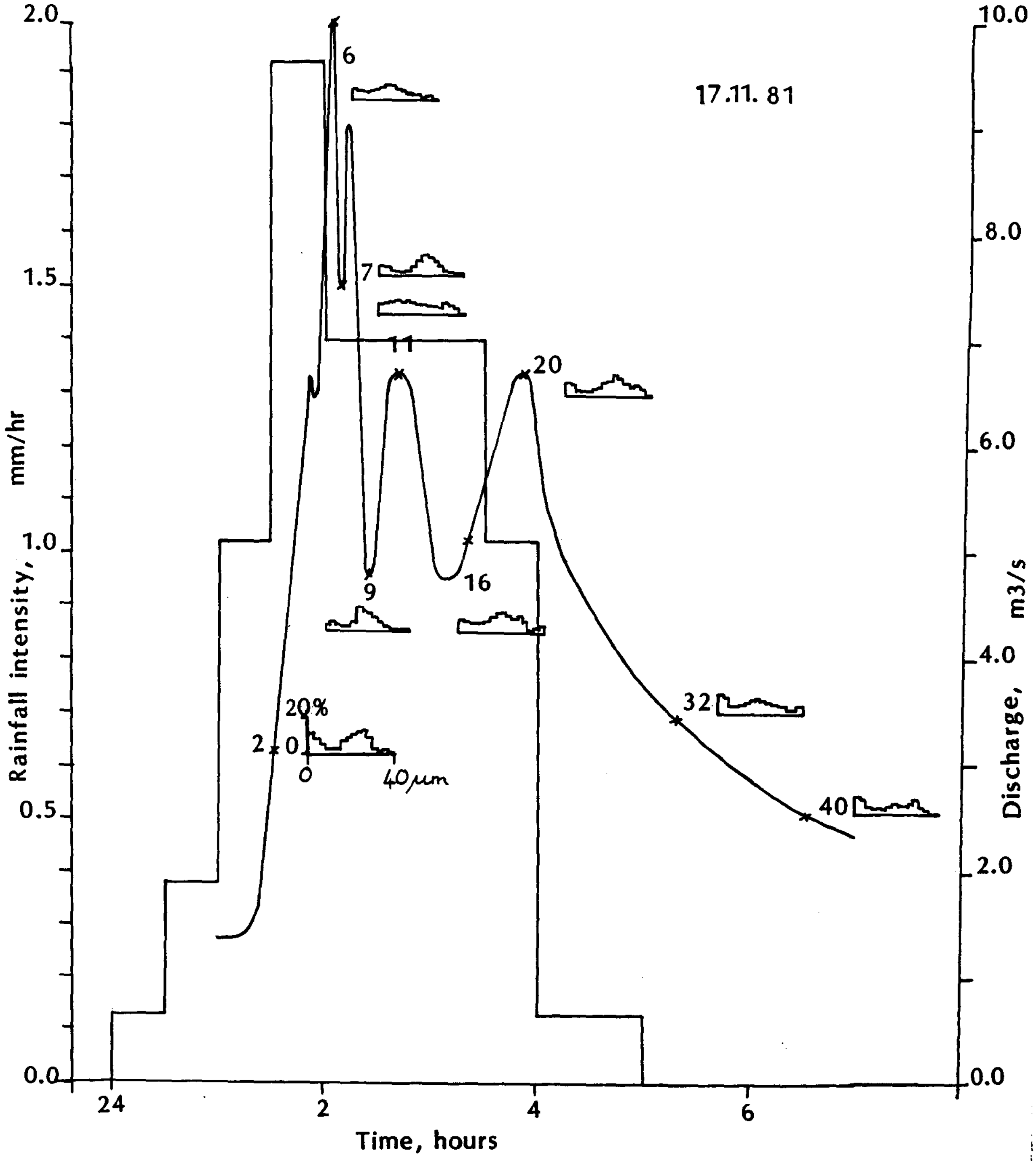
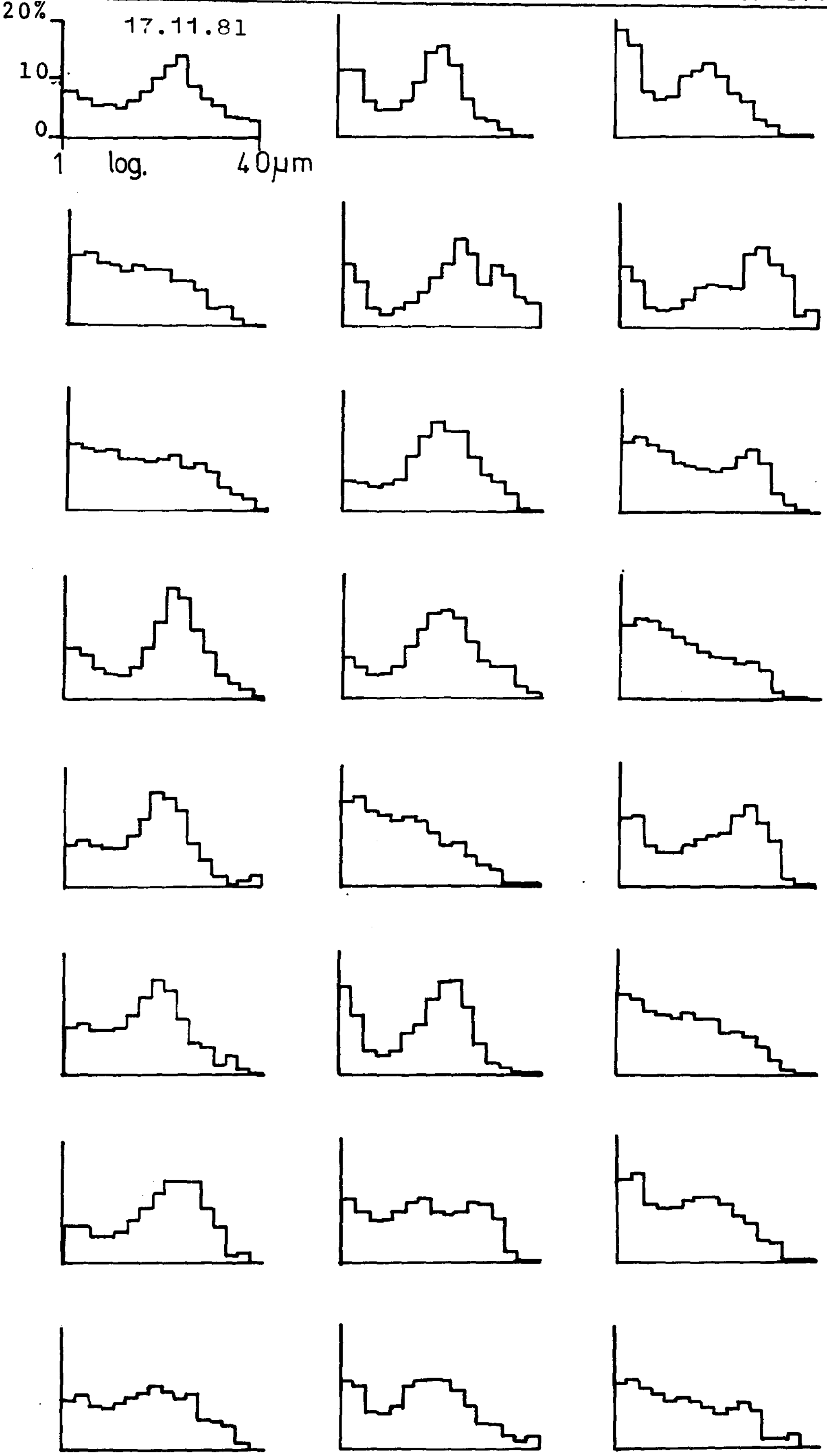


FIGURE 5.16

PARTICLE SIZE DISTRIBUTIONS OF MIXED-GROUP STORMS.



PART III

SURFACE TEXTURE ANALYSIS

CHAPTER 6

THE EXAMINATION OF SEDIMENTS BY SCANNING ELECTRON MICROSCOPY.

6.1. Introduction

The aim of this chapter is to introduce the use of the scanning electron microscope in the study of sediment surface textures and, particularly, in the study of the stormwater sediments. Scanning electron microscopy plays the major role in this examination of stormwater sediments: clear images are obtained enabling a thorough analysis of the shape and appearance of the surface features of the particles. The particles are too small for the same results to be obtained by the more conventional, lower magnification light microscopes. The method of sample preparation, the mode of operation of the microscope for this analysis, and the photographic techniques involved are described.

One of the main aims in analysing the surface textures was to produce quantitative results, rather than the qualitative descriptions of previous studies, and to examine the relationship between the features and the processes of the sediment transport history.

Although microscopic surface textures of sediment have been described previously, both with the scanning electron microscope and other methods (Cailleux, 1942) quantitative work has been minimal. Attempts have been made to overcome the technical problems of making accurate measurements of features from photomicrographs (Tovey and Wong, 1973; Goudie and Bull, 1984) but little work has been done on quantifying either the number of surface features or the area of the particle they cover. In this study, describing the features as a percentage of the total grain area both provides quantitative results and largely eliminates the inadequacies of the photomicrograph, such as distortion and lack of relief, that hindered Tovey and Wong's (1973) method. From the results of the percentage area per feature, the features can be classified and the dominant features, or those occurring as suites of features, become evident and can be classified. In this way features common to different environments and processes emerge. The aim then was to classify the stormwater sediment according to its origin in the catchment by comparison with similar studies of particles of known origin. Features attributed to the origin of the sediment became modified by the transport history as described below.

In this study the features have been described largely according to Krinsley and Doornkamp (1973) and Bull (1978b) and are listed in Tables 7.1. and 7.3. As these authors described geological sediments a number of additional features have been introduced which apply to this urban environment. Further, it is important to note that almost all the sediment described in the literature is of sand-size. The stormwater sediments are silt-sized and the effects of abrasion and feature formation compared with the larger particles is not clear. However, the features observed on the stormwater sediments appear to be very similar to those on sand-sized grains and their similarity of quartz mineralogy makes this probable. There is some question however as to whether silt-sized particles are truly abraded or simply break along cleavage lines. Once again, quartz is resistant and evidence of stormwater sediment indicates true abrasion.

Variations in surface textures were studied for different land uses around the catchment and progressive changes were studied along the storm drain and at the outfall during storms. It was hypothesised that if the texture could be quantitatively described and classified for a particle sampled at its origin, and then for similar particles collected at different points during drain transport, the effects of the transport could be deduced. The texture variations studied during storms were related to the rise and fall in discharge, to the entrainment capacity of the rainfall and antecedent conditions, and to the dominant processes of alteration operating in the drain during the different storms.

6.2. A Summary of Environmental Studies Relevant to Stormwater Sediment Analysis.

6.2.1. Introduction

Literature on the study of sediments with the scanning electron microscope was first published in the late 1960's and early 1970's. From then there followed a gradual increase in the number of papers produced through the 1970's, notably by Krinsley and co-workers, until a large peak was created by contributions to Whalley (ed) (1978) in which the scanning microscope in the study of sediments was discussed.

Quartz sand grains have been the most frequently described sediments as a result of their widespread occurrence throughout the world. Krinsley and Doornkamp (1973) produced probably the most definitive work on surface textures of quartz sand grains from which authors in the field have subsequently taken their nomenclature. In such subjective studies the standardisation of nomenclature was vital for the comparison of case studies of different wording.

Initially, specific features were related by workers to the environmental processes at the sample site. Variations in the size and density of similarly shaped features were related to the total energy of the process acting on the sediment at that point in the system. This relationship includes the energy acting on a static sediment, for example chemical solution in soils; the size and density of features appears to increase with the length of time the sediment is exposed to the process (Douglas and Platt, 1977). Another example is the abrasion of sediment in a river-borne load then particles are abraded both against the bed and each other. Time plays an important part in the density of the features as a function of the distance travelled by the grain may be related to feature density, and feature orientation to the direction of travel.

Only lately in the literature have authors suggested some of the features viewed may be relict from those originally created during diagenesis although many studies had examined the superimpositions of features on grains which have passed through two or more environments (Blanche and Whitaker, 1978; Margolis and Krinsley, 1974; Middleton and Davis, 1979; Bull, 1981). It seems safe to assume that the most complete and most widespread features are the product of the most recent environment but it is not known how long a texture lasts before being obliterated by successive features. Here again the process is dependent upon the relative degrees of energy of the previous and present environments. Investigations along these lines still need to be quantified much more fully.

Various attempts have been made at the laboratory simulation of features to enable the controlled energy of the process to be related to the size of the features it produces. (Robson, 1978; Krinsley, Leach, Greely and Mckee, 1979; Wilson, 1979; Krinsley and Wellendorf, 1980; Lindé and Mycielska-Dowgiałło, 1980). A number of features occur in more than one environment. As a result a suite of features, rather than a single one, is diagnostic of each environment. However there remains the need to accurately measure the energy of the environment and to relate that to texture parameters.

6.2.2. Features of Littoral Environments.

Although no literature has specifically dealt with the surface textures of urban stormwater sediments many of the features observed are similar to those found in environments with comparable hydrological processes. The features are described here and are referred to in the following chapters when the stormwater sediments are discussed. Of these features the littoral beach zone, of active abrasion by vigorous water movement, most closely resembles the drainflow environment.

The following features were attributed to littoral environments by Krinsley and Doornkamp (1973) and in many cases are very similar to the dominant features of the stormwater sediment. Mechanically-formed 'V' notches are common features of high energy, abrading, subaqueous environments. This type of impact pit is triangular in plan view and irregularly orientated. 'V' notches have been found on smooth, rounded grains which are usually the most resistant to all but these strongest impacts. 'V' notches occur too on fresh surfaces but usually on cleavage planes where the impacts instigate the breakage along the cleavage planes. Straight or slightly curved grooves of 1 to 15μm occur less frequently, but in the same regions as 'V' notches. They are probably the result of scratching, on impact, by the sharp edge of one grain across the face of another. (Krinsley and Margolis, 1969). The areas left as relatively smooth convex surfaces are termed "upturned plates" and are mechanically formed in as much as they remain when the surrounding surface has been abraded.* Krinsley and Takahashi (1962b), in their studies on grains abraded in a simulated beach environment, showed that the 'V' notches were produced by the interparticle collisions of a turbid fluvial environment. Conchoidal fracture, a feature occurring abundantly in most environments, is less common on stormwater sediments where it appears as a clearly visible breakage or impact feature. A feature of varying size, it occurs in the form of arc or semi-circular shaped steps and was duplicated in a simulated beach environment by Krinsley and Donahue (1968a). These features are discussed further below (Section 6.2.3).

In comparatively low energy regions of littoral environments features are formed by chemical processes (Margolis, 1968). In contrast to the mechanically-formed 'V' notches, chemically etched 'V' notches are highly orientated. Solution is most extensive along the weakest crystallographic axis (Margolis, 1968; Lin, Rohrlich and Slatkine, 1974; Lindé and Mycielska-Dowgiałło, 1980) thus the longest side of the pit occurs along the 'c' axis. 'v' shaped pits created by solution usually have a much smoother profile than mechanically formed pits as shown

* Lorey (1978) describes upturned plates as being formed by the alternate silica precipitation and wind abrasion on fine particles.

in Figure 6.1 (after Margolis and Krinsley, 1974).

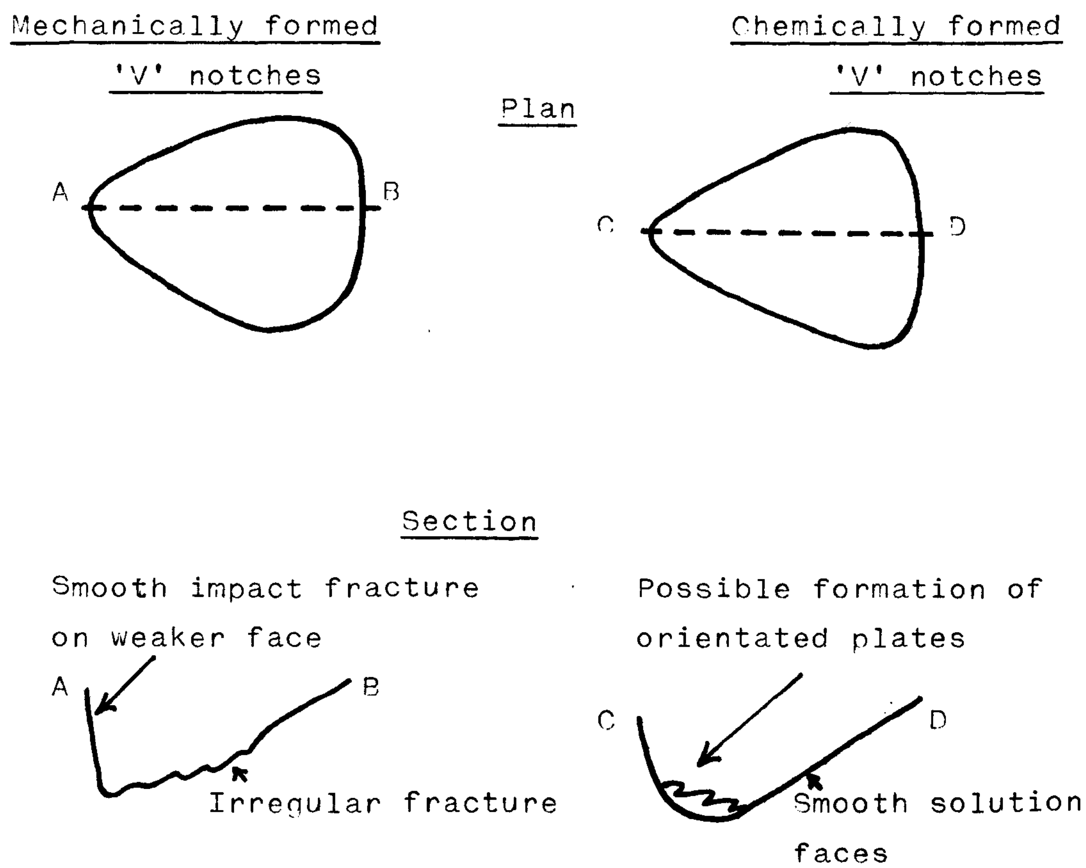
6.2.3. Conchoidal Fractures.

Conchoidal fractures are the commonest particle texture on non-transported grus. On transported sediment they occur as breakage, rather than impact, features or as relict features from grus. Lines of conchoidal fractures, of uniform size, spacing and orientation have been termed "chattermarks" (Folk, 1975). Trails of chattermarks may lie in different orientations on a particle surface and even cross each other. Although Folk (1975) recognised these features on garnets from glacial environments, they have also been recognised on quartz grains from fluvial environments by a number of authors and in this study are found to a very limited extent on the stormwater sediments. There is controversy over whether these features are formed mechanically or chemically; Bull (1978a) claimed chattermarks were of chemical origin on quartz grains while Folk maintained those on garnet were of mechanical origin. Gravenov, McLelwain and Stuparsky (1978) found chattermarks on soft minerals but absent from garnet grains in the same sample and produced chemically etched chattermarks on the soft minerals but not on garnet, using phosphoric acid. Rocha-Campos and Krauspenhar (1978) found chattermark trails on water borne quartz grains but ten times smaller than those previously recorded. In reply Folk (1978) suggested that the different sizes may be the result of different environments and that garnet from a variety of environments needed to be studied. He hypothesised firstly, that marks on garnets are almost exclusively of glacial origin and secondly, that they are shorter on quartz due to a lesser impact than a prolonged scratch. The argument remains unsettled but it would seem that such chattermarks as Folk found require the extreme force of glacial processes to make an impression on garnet whereas lower energy environments may produce similar features on softer grains.

FIGURE 6.1.

A COMPARISON OF MECHANICALLY AND CHEMICALLY FORMED 'V' NOTCHES

(After Krinsley and Doornkamp, 1973, and Margolis and Krinsley, 1974)



It is important to remember that a number of features are formed in any environment and some features are formed in more than one type of environment. Features occur on the particles in suites which are diagnostic of the environment in which they were formed and the processes operating there.

6.2.4. Airborne Particles.

Some of the stormwater sediment originates amongst the airborne particles in the catchment. Spherical particles of flyash, mainly from industrial chimney emissions, are the most distinctive, and angular quartz fragments are common. The literature on airborne sediment surface textures has largely described the aeolian particles of desert dunes and loess but some similar features have been found on airborne material in air pollution studies. The early workers recognised the progressive rounding and size reduction of grains in wind transport. Looking at a variety of minerals, Marshland and Woodruff (1937) showed that the effects of wind transport depended on the mineral hardness with the exception of minerals with extensive cleavage which broke down more readily than softer, less highly cleaved grains. Cailleux (1942) and Bond (1954) suggested the age of the grains could be gauged by the degree of roundings and Krinsley and Takahashi (1962b) simulated the rounding process showing they were produced by interparticle collisions. Smalley and Vita-Finzi (1967) concentrated on the reduction in size of grains in wind transport which was particularly noticeable because of their glacial origin as relatively coarse grains. Frosting was the term used to describe the grain surface texture by the early workers, for example Bond (1954) and Lucchi (1970). It probably encompassed the features described in detail later with the aid of the scanning electron microscope. Frosting is the term now more widely used in the description of precipitated microcrystalline quartz.

The terminology describing aeolian features was initially adopted by Krinsley and Doornkamp (1973). The list of features comprises, upturned plates of precipitated silica, a smooth silica precipitation surface, an irregular solution-precipitation silica surface, surface disintegration by solution or by salt crystal growth, dish-shaped concavities, mechanically formed upturned plates (further described by Krinsley and Wellendorf, 1980) rounded grains and adhering particles. The exact nature and process of formation of upturned plates is still unclear. Le Ribault (1978) studied the processes which caused some of these features and by relating those features to the energy of the environment, found high density crescentic impact features in high energy conditions and impact features of clean faces and sharp edges in low energy areas.

Krinsley and co-workers attempted to study experimentally the relationship between form and process. McKee, Greely and Krinsley (1979), using a range of artificial wind speeds measured the size of the impact pits thus created and related the two. In addition clay-sized fragments were abraded after cracks were formed around the impact pits, particularly at higher velocities. Krinsley and Wellendorf (1980) simulated four wind speeds commonly occurring in the Sahara. The results showed that the spacing of upturned plates was constant across individual grains and was comparable for similar wind velocities. The spacing seemed unaffected by the grain size in the order of 200 to 300μm studied.

The spherical airborne particles with uniform surfaces of upturned plates are usually the most distinctive type of airborne sediment found in aeolian environments and closely resemble those spherical particles found among the stormwater sediments although they are more likely to be flyash in this environment (Chapter 3; Gibbon, 1979; Lindé and Mycielska-Dowgiałło, 1980). Another high energy feature, observed on airborne sediment collected in stormwater, is the plastered silica on angular fresh faced particles and it has been attributed to high energy impacts (Whalley and Krinsley, 1974). These authors studied the feature in glacial environments but it is the influence of the high energy impact, common to both environments, which is the common factor. Further aeolian and fluvial features solely of the urban stormwater system are given in Chapters3 and 7.

6.2.5. The Effect of Grain Size and Mineralogy on Surface Textures.

Although the vast majority of the literature has been concentrated on quartz, sand-sized particles, it is important to consider other mineralogies and particle sizes where relevant to the stormwater sediments.

Marshland and Woodruff (1937) studied the effects of simulated wind abrasion on a selection of minerals covering a range of hardness values. However the studies of the ubiquitous quartz sand grains seemed to generate further similar studies, particularly in the wake of Krinsley and co-workers, at the expense of other minerals and particle sizes. Some authors such as Setlow (1971) possibly felt the approach was justified after their studies of other minerals showed that the same feature suites were present on all minerals in the same environment. Similarly, Bull (1978a) found that clay and silt-sized particles exhibited the same features as their larger counterparts, and occurred in any shape.

In contradiction to Bull's (1978a) findings, Krinsley (1978) found "vast differences in texture and shape with decreases in grain size". Quartz silt grains were much flatter and more angular than sand grains and it was suggested that the increased dominance of cleavage on the form of fine particles causes this shaping. A more frequent occurrence of flat precipitation silica surfaces was also found. This was quite likely to be optically continous with the granular quartz which was crystalline out to the edges of particles as small as 0.25μm diameter.

The stormwater sediment studies have borne out the conclusions of both Bull (1978a) and Krinsley (1978) to some extent. As described below no other element, except sulphur, appeared to have a distinctly recognisable suite of features. Although there is undoubtedly a great variety of particle mineralogy around the catchment, the majority of the particles reaching the outfall were quartz therefore the question of cleavage breaks is only of minimal importance in this study. The question of size may be relevant as the stormwater sediment is silt-sized but the features observed appear to be very similar to those described in the literature for sand-sized quartz grains. As mentioned in the introduction, if the silt-sized grains were of a weaker mineralogy than quartz impact might cause cleavage breaks rather than impact features. Possibly on some occasions small particles are displaced on contact with larger ones, thus suffering minimal erosion, but this is not proven. Often the fine grains, although in turbulent flow, will tend to be carried higher in the flow than the larger grains of the same density and thus the particle interrelations are similar to those of larger grains although the strength of impact may be a little less.

Regarding the significance of grain mineralogy, some work was initially carried out on the stormwater sediments to discover their elemental constituents. The energy dispersive x-ray analysis technique (EDXA) was used to produce the element spectrum for a spot on the grain. Repeated trials almost always (80 to 90% of trials) gave the same results. Silica and aluminium peaks were dominant with subsidiary peaks of magnesium, sulphur, phosphorus, potassium, clacium, iron and occasionally titanium. A small proportion of grains gave a slightly enhanced iron peak but of a lesser magnitude than that of silicon or aluminium. Very occasionally, a larger sulphur peak would occur, or some of the subsidiary peaks would appear to be insignificant from the background (Plates Chapter 7). Of over 100 particles and their elemental counts examined, the only correlation found between texture and elemental count was that of precipitation and solution features and silica. However, as the silicon peak was dominantly high this was not conclusive. Rather, it confirms the dominant presence of quartz particles. Particles of other elements for example iron, had no surface texture in common and as such the elemental count had no diagnostic value in determining the sediment mineralogy from its appearance. The only exception was the background appearance of sulphur in some airborne sediments.

6.3. The Precipitation and Solution of Silica.

Silica precipitation and solution deserve a special mention because of their widespread occurrence on the stormwater sediments and the major role they play in the progressive alteration of the sediment during transport along the drain during storms. Here, a review is presented of the studies of precipitated silica on grains in fluvial and lithological environments which have some bearing on the origin and transport history of the urban stormwater sediments. The particles may be transported in the stormwater in large flocs of organic material (Chapter 3, Ellis, 1979) but it is the inorganic processes affecting individual grains which are discussed here.

A review of the literature on the processes causing silica solution and subsequent precipitation as overgrowths, revealed three favoured hypotheses: solution, pressure solution and silica dust generation.

Solution processes have been described in recent surface sediments such as low energy beaches (Lin, Rohlich and Slatkine, 1974), soils (Doornkamp, 1974; Douglas and Platt, 1977), detrital quartz weathering in sandy sedimentary deposits (Austin, 1973; Marzolf, 1975), moraines (Whalley, 1974), and granite grus (Baynes and Dearman, 1978). Lin, Rohrlich and Slatkine (1974) described the process as quartz solution and ionisation to silicic acid in an alkaline, subaqueous environment. Krauskopf (1959) showed experimentally that silica is soluble at pH9 and above, a condition most often found in localised areas of trapped pore water particularly if evaporation concentrates the pore water further (Le Ribault 1978). Le Ribault (1978) studied the effects of silica solution and precipitation in the controlled environment of soil horizons where any textural responses to change were purely chemical. In the horizon of silica solution a layer of silica peeled off, particularly in hollows with an aqueous solution under-saturated in silica. More vigorous solution resulted in geometrically orientated features. Similarly, Baynes and Dearman (1978a) found granite with a high content of feldspars decomposed first along cracks and in pores where silica in solution was one of the weathering products. The continued replenishment of pore water maintains the solution process (Blanche and Whitaker, 1978).

Silica in solution, in pore water or circulating ground waters, precipitates out of supersaturated waters according to Austin (1973), and at high pH according to Doornkamp (1974) and Whalley (1974). Whalley (1974) suggested the redeposition of quartz formed bonds between quartz grains where point contacts between grains provided the localised high pH of interstitial water next to mafic minerals. Marzolf (1975) in addition to pH, found silica precipitation dependent upon temperature and the partial pressure of carbon dioxide. More specifically, Grant and White (1978) found rapid precipitation at saturation point, 140ppm, at 25°c and stressed the importance of aluminium concentration. Under such conditions Werle and Schneider (1978) found pore space reduced by silica precipitation. As in his solution study above Le Ribault (1978) found precipitation features, in this case "globular" deposits on sand grains, could only be the result of these chemical processes.

Any effects of pressure solution are unlikely to have remained on the stormwater sediments but the process is mentioned here for the sake of completness of the development theories.

Pressure solution only occurs under the considerable pressures during the diagenesis of sediments buried at depths of at least 800m (Whalley 1978), a principle agreed upon by Pittman (1972) and Wilson (1980). Pittman (1972) argued that the pressure solution of silica is concentrated under the increased stress of grain contacts leading to pore infilling by silica in the adjacent lower pressure areas. Whalley (1978) considered at least some of the silica in overgrowths to be of biochemical origin, from pressure solution in regions of volcanic and thermal springs where the reaction was enhanced by the fluid warmth.

A number of authors considered the secondary silica in the formation of overgrowths was derived from silica dust. The dust was generally thought to be generated from grain fracture during diagenesis (Waugh, 1965; Steinen, 1978) and the weathering of clay silicates (Waugh, 1970). However, Burdman (1962) suggested it might be the result of wind abrasion. The currently most widely held view (Smalley, 1971) is that silica dust is the result of sand grain breakdown in igneous rocks. Under conditions of decreasing volume and increasing density, stresses are set up which produce intense fractures due to the quartz crystallography; the grains decompose to dust. Steinen (1978) found it formed a cement during diagenesis which reduced the porosity of the sediment; whereas Higgs (1979) thought it formed the overgrowths adhering to quartz grains as flakes or crumbs.

The exact cause of silica generation with sediments appears to depend on the age and position of the sediment. Solution of silica was shown to be prevalent in recent sediments; 'recent' both in terms of soils and moraines, and of recent geological sediments exposed at the earth's surface, that is sediments allowing the circulation of pore water. Pressure solution was a process requiring the extremely high pressures only known to be available at depths of approximately 1km in the earth's surface. In both types of solution some increase in temperature was thought to act as a catalyst. The occurrence of silicaceous dust seems undisputed and again is associated with diagenesis but in an abrasive context.

Where solution processes are at work silica appears to be precipitated when the solution reaches appropriate conditions of silica concentration, pH temperature and the partial pressure of carbon dioxide. This was usually the result of transport in circulating waters or the easing of the high pressure conditions which caused pressure solution. The deposition of silica dust seemed similar to the last, being removed from the high pressure area of grain abrasion.

Overgrowth formation is common to the later stages of silica precipitation in most environments but there are a few theories of overgrowth development which are outlined here. Waugh (1965) described the development of overgrowths in a manner also recognised by Pittman (1972) and Marzolf (1975). Secondary silica appeared first in cemented clusters and rhombohedral projections of 1 to 12μm diameter with smooth crystal faces. The rhombohedra, overlapping, formed planar faces which finally grew into prismatic, euhedral crystals. Precipitation first occurred on the grain corners, then on the outer rims of upturned plates until the plates, and eventually the entire surface, were covered. Wilson (1978a; 1980) looked at Waugh's (1965) stages of overgrowths in more detail and found that the crystal lattice orientation of the host grain determined the growth direction of overgrowths. The crystals grew uniformly where space permitted until they merged and overlapped, then forming larger crystal faces and finally one crystal. In reality this ideal was liable to be interrupted by the superimposition of various stages. Where this development was discontinuous with time, Austin (1973) found successive layers of overgrowth separated by detrital material.

There have been descriptions of solution and precipitation features on almost every conceivable part of the grain surface. The most common in lithological and fluvial environments are; plates, corners, edges and hollows. Doornkamp (1974) and Le Ribault (1978) found silica precipitation on the plain faces of particles in soils. In their glacial studies, Whalley and Krinsley (1974) too found silica, in the early stages of precipitation in the form of microcrystalline frosting on plain surfaces, corners and fresh cleavage plains. Both Whalley and Krinsley (1974) and Le Ribault (1978) found silica solution was concentrated in hollows, or depressions in the grain surface in trapped water and in some cases Le Ribault (1978) found silica precipitated as highly orientated features in the hollows which probably occurred on the drying of trapped water. Looking at sands, probably of Jurassic age, Marzolf (1975) found precipitation features as regular frostings on the rims of hollows which were of geometric outline. In areas of strong weathering Waugh (1970) found crystallographic orientation of detrital quartz grains predominantly along the weakest 'c' axis whereas Baynes and Dearman (1978) found silica precipitation on grus surfaces. In recent sediments Whalley (1974, 1978) and Whalley, McGreevy and Summerfield (1982) found silica precipitated rapidly as non-crystalline interparticle cement whereas in diagenetic sandstones and orthoquartsites the grains were held together by quartz-crystal interlocking growth. An attempt was made to draw some correlations from these findings regarding process and environment.

Once the first solution of silica has produced grain surface depressions the process is enhanced there by trapped water which becomes increasingly alkaline from the solution of silica and other elements. Silica precipitates out first on the rims and later in the hollows as the water evaporates. Plain surface deposition seems more common from circulating waters. There is no direct relationship between these processes and their environments although early microcrystalline stages occur alone in recent sediments and near surface sediments such as soils. Diagenetic sediments however have more advanced crystallographic overgrowths resulting from their buried, undisturbed positions which have remained thus for a considerable period of time. Waugh (1965, 1970) and Austin (1973) found the overgrowths were optically continuous with the quartz in the 'host' grain; indeed, the propensity for continued crystal growth in the substrate lead to the precipitation of silica at those points on the grain surface. However, it is not known whether or not this is the universal case. In laboratory simulations using sand and rapid water evaporation, Whalley (1978) found silica precipitated quickly but, unusually was not optically continuous with the substrate. In many studies where the precipitation of silica has been observed on the grain surfaces no mention has been made of the relationship with the host grain. If the influence of the host grain can be examined progress can be made in showing more clearly the mechanisms of silica solution and precipitation and what determines their positions of occurrence.

Silica is commonly precipitated on particle faces and in protected hollows in the stormwater sediment; the edges suffer more predominantly from abrasion. Precipitates extend to cover large areas of particle surfaces and develop to some depth. Simultaneously it appears that the precipitation surfaces are attacked by solution. In isolated cases of extremely low energy conditions, such as the drying out of the drain, the precipitates develop clear crystal form. Whether or not any of these precipitates are optically continuous with the host grain is not clear. Small scale precipitation occurs on fine individual particles almost engulfing the fine grains. These and larger particles become cemented together by the precipitated silica into aggregates. The process of precipitation may begin in the gutter at the first opportunity for runoff to be collected and to be stationary or slow flowing. (This is clearly not the case in intense initial rainfall). Subsequently, particles undergo more rapid precipitation during drain transport. The pattern of development is similar to that described in the literature but the time scale is generally much shorter. Where sediment has rested for sufficient time in a low energy littoral region, surface textures have developed from the precipitation of silica from the water. Such features are usually found with the effects of subsequent solution creating a convoluted precipitation-solution surface. In some cases it is difficult to distinguish between an embryo precipitation surface and one that has suffered from considerable solution. The exception is in instances where sediment has lain undisturbed long enough to allow recognisable crystal growth (Margolis and Krinsley, 1974).

Soil aggregates, with precipitated silica, of the kind described above occur in the catchment but the majority of surface sediment comprises frésh-faced, angular particles which undergo rapid precipitation during drain transport. The pattern of development is similar to that described in the literature but the time scale is generally much shorter in the stormwater system.

6.4. The Effect on Textures of the Energy of the Environment.

From the studies of grain surface textures in different types of environment and from similar environments but of different scales, it becomes clear that the size and density of the features formed depends very much on the energy level of that environment. In an environment where high levels of energy are created and expended the features will be both numerous and well-developed, in contrast to low energy conditions.

From the examination of the modifications of quartz grains by their transport media, Margolis (1968) and Blackwelder and Pilkey (1972) used the dimensions of features as in index of the environmental energy levels prevalent during feature formation. The results, described in greatest detail by Margolis (1968), have shown that orientated etch pits were found in areas of low wave energy, having been created by sea-water solution of the crystal surfaces. Sand surfaces from moderate energy areas comprised a mixture of chemically-formed pits and impact pits and it was the impact pits which dominated the high energy areas. It was concluded that the relative numbers of each feature at each energy level can be used to deduce the energy conditions in ancient shorelines. Blackwelder and Pilkey (1972), also attempted to link the orientation of the features to the direction of travel in water currents and suggested a tenuous relationship with the origin which was traced upstream on the evidence of feature orientation.

Using more stringent statistical techniques, Shawa (1973) and Baker (1976) calculated the parameters: mean, standard deviation skewness and Kurtosis of the distributions of selected surface textures. These results, studied in conjunction with particle size and environmental data, showed that the changing energy levels of the transport cycles were associated with feature type and size. Shawa (1973) traced the history of sediment, from a continental shelf deposit through its reworking from a nearshore marine deposit, using the varying feature relief caused by different environmental energy levels. Each sedimentary process had a range of energy levels, turbulence and viscosity, depending on the medium. In Baker's (1976) study to show quantitatively which features were the most closely dependent upon the environment, only four features were distinctive statistically: grooves, scratches, and mechanical and chemical 'V' notches. The occurrence of greater than 50% of the features being of this type indicated a coastal environment; less than 30% indicated desert with the influence of a fluvial history; less than 50% meant rivers and more than 50% pointed to high energy beaches. Cracks and chemical 'v' notches on desert grains are smaller than those from other sources because of the low energy, periodic subaqueous environment, whereas mechanical 'V' notches increased off-shore into deep water. Initially, the study involved many more features found in suites as described by Krinsley and Doornkamp (1973). However, in an effort to analyse the environment of the grains studied, the statistically high numbers of the particles required necessarily reduced the number of features which could be analysed. This was understandable but unfortunate in the light of the knowledge that features occurring on suites represent environments rather than a large number of one type of feature.

6.5. The Transport Histories of Sediments.

Features observed on grain surfaces tend to be attributed largely to the environments in which the sediment was found. It is unclear however how quickly or completely features are superimposed when a particle moves to a new environment. It depends to some extent on the environments involved and the mineralogy of the particle; a high energy environment would most rapidly superimpose its characteristic features on sediment of soft mineralogy. It remains unclear however to what extent relict features can be found on particles. This section explores the use of surface textures in tracing the transport history of sediment.

It is assumed that grain surface textures represent a mixture of the most recent and, or, the most dominant weathering or erosion processes (Porter, 1962); the most complete features being the most recent (Krinsley and Schneck, 1964). Thus, the superimposition of features indicates the order of successive transport histories (Steiglitz, 1969). Instances have been reported of all possible combinations of transport cycles between fluvial, glacial and aeolian environments as well as the degree of persistance of the original diagenetic features. The extent of the effect of the transport processes on grain surfaces depends on the mineralogy, size and shape of the grain, the ease of fracture of the parent material, and the energy of the transporting medium (Whalley, 1979).

Changing energy levels and regions of transport, within the same fluvial system, have been traced using the size and density of surface features, usually 'V' notches, and an attempt was made by Blackwelder and Pilkey (1972) to deduce the origin of the sediment by this method. These authors were particularly interested in the apparent link between the feature orientation and the direction of transport. Their results were borne out when Manker and Ponder (1978) calculated correlation coefficients for the distance of transport and the area of the grain surface occupied by specific features. The size of the feature depends on the transport mechanism and the distance travelled. The grain concentration affects the collision frequences; for example, collisions and feature formation are more common in the traction rather than suspension load.

Studies of changes in the erosion cycle of sediments have shown differences of process between the flow and ebb tides, indicated clearly by the rapid response of solution and precipitation processes respectively (Le Ribault,1978). Solution continues in trapped water as the tide ebbs but gives way to precipitation once saturation point is reached and is hastened by evaporation of the water.

The result of fluvial transport entraining aeolian sediments was the removal of upturned plates (Le Ribault,1978) and the superimposition of littoral 'V' form impact pits, which increase with the distance off-shore (Strass,1978). Both authors described the corrosion from the impacts of grain collision, particularly on broken grain edges, and both followed the passages of their sediment to the immobilised positions in soil and till respectively, where silica solution and precipitation became the dominant processes.

The severe angularity is a common feature of both the road grain constituents of the stormwater and the glacial sediment as described in the literature. It is therefore useful to note those changes found on grains after a change from glacial to fluvial transporting agents. The features in both cases were caused by abrasion so appear similar on both types of sediment. Examined in detail however fluvial-caused features are generally smaller, due to the lower energy process, and present on softer minerals which would have been entirely eroded away by the equivalent glacial processes (Rocha-Carmpos and Krauspenhar; 1978).

Rounding and size reduction of the initially very angular grains seemed to occur only after several kilometers of river transport (Whalley, 1979 and Smalley and Vita Finzi, 1967, respectively) which would account for the persistance of angular storm sediments after short transport distances.

It was some time before authors considered the possibility of original diagenetic surface features surviving more recent transport cycles. If the correlation between environmental energy levels and feature type and magnitude were to be proved wrong, Margolis (1968) was prepared to believe the features present may be a remnant of the original features of the parent material. This was a rather backhanded approach to the question; a more commonly held view on the subject was that the original features of a grain surface must be known, to be certain that the remainder were related to transport mechanism (Scholle and Hoyt, 1973). However there were some more controversial suggestions. For example, Ingersoll (1974) from detailed measurements of 'V' notches, concluded they were of diagenetic origin despite their subsequent period of transport in a high energy beach environment. These results are difficult to dispute since there is no definite measure of feature development with the time or energy of the transport medium. However in this case, where the high energy beach environment is probably the most efficient abrasive agent of surface textures, the implication is that the original features persist almost indefinitely. To be fair, Middleton and Davis (1979) did find some relict features on intertidal bars, but again there is no indication of the time period since erosion from the parent material. In a similar vein Wilson (1980) argued that overgrowths and etched features were of diagenetic origin, rather than recent, although, if the same type of features are being studied this appears to contradict Le Ribault's (1978) findings that such features are the most rapid indicators of changes in the environment.

In bed-rock studies with limited or no transport processes, the contradictions are less important and the original features have proved useful in lithological studies. Examining a transition zone across an upper Cretaceous boundary, Krinsley and Schneck (1964) used grain surface features to determine the exact position of the boundary. 'V' notches were found reminiscent of fluvial transport in the surf zone but were fewer and less pronounced than their modern counterparts. In this case the grains have remained in situ since their deposition and compaction, subject only to mild chemical processes.

The origins of the surface features are thus fairly certain. The question remains of the energy and time required to replace a grain surface texture of known hardness and relief.

6.6. The Selection and Preparation of Stormwater Samples for Scanning Electron Microscopy.

6.6.1. Sample Selection.

In previous studies samples of particles for scanning electron microscope examination have been collected in large numbers from air or liquid filtration. Alternatively, fewer, usually relatively larger, particles have been placed individually on the mounting substrate using a mounting needle with or without the aid of a binocular light microscope. In addition, several authors adapted the samples initially prepared either for transmission electron microscopy or in the study of soils, from thin sections.

In this study airborne particles were collected in a dry state under vacuum, on nucleopore polycarbonate filters mounted in a filter funnel placed vertically facing the prevailing wind. The particles were not very firmly held on the filters and therefore required careful handling.

Trials were conducted in picking up particles on sticky tape but the coarser particles preferentially adhered and futher attempts to collect the fine material produced too great a density of sediment on the tape. The immersion of the sediment in distilled water followed by filtering, as described below, was more satisfactory. A dispersing agent was added to the sample but it had no noticeable advantageous effect on the distribution of the particles on the filter.

6.6.2. Filtration.

King and Banholzer (1978) described in detail the precautions taken in their method of filtering and mounting samples for scanning electron microscopy which they maintained lead to the most accurate measurements. The entire operation was done by fluid dispersion employing pre-filtered nanno-grade toluene which had no effect on the particles. The method involved thorough cleaning at every stage and provided for the easy recognition of contaminant particles. An elemental spectrum was recorded both before and after the first sample to deduce the extent of contamination left after sample analysis.

Another detailed study of sample preparation for scanning electron microscopy is that of Le Guen, Rooker and Vaughan (1980). The technique is similar to that used in the early stages of this study of stormwater sediments and is further described in Hamilton, Roberts and Ellis (1981). The aim of Le Guen, Rooker and Vaughan (1980) was to be able to transfer samples from the optical microscope to the scanning electron microscope on a flat and featureless surface of minimal background elemental count. For this reason the more common fibrous millipore membrane filters were not usually used although the authors found them considerably more robust than the flat, featureless nucleopore filters. In addition very fine particles were entrapped within the upper layers of the fibres which would have obscured the full view of those particles. The formation of a carbon replica and the subsequent dissolving of the filter was time-consuming and unsuccessful. Despite a number of problems of nucleopore filters, described below, the flat surface was a great advantage and the circular apertures were easily recognisable. The preparation method involved laying a filter, sample side up, in cleaning solution placed on a glass slide. The filter was dried and collapsed by 15% of the original thickness to form a permanent thin transparent plastic film with the embedded sample. The filter was then etched in plasma for optical examination, freed from the glass slide and mounted on a stub for electron microscope examination. The etching time of 7 minutes, determined by trial and error, left the particles clear of the filter matrix and exposed any small particles (less than 1µm) trapped originally in the upper layers of the filter. The composition of the filter was important, for example, a filter of mixed cellulose, acetate and nitrate collapsed under the impact of of the beam. Further problems involved in the use of nucleopore filters included the movement of particles on the filter, the loss of particles during handling, a reduced count rate resulting from inefficient filtering, electrostatic forces causing the filters to curl, and the unsuitability of the filters for the sampling of fast moving air due to their resistance and fragility. Contrary to these findings Hamilton, Roberts and Ellis (1981) found nucleopore filters gave good results when used in both air or water and in both cases under vacuum in firm sample holders. Samples were stored under vacuum and stood up well to mounting and coating procedures. Occasionally filters were found to curl up when dried too rapidly. Sediment movement occurred when the particle density was too great and when rapid drying caused adhering particles to flake off the filter. For the analysis of the majority of the stormwater sediments under discussion here the size range of 1 to 40µm was too low for light microscopy and the method unnecessarily complicated. It was however of considerable use in examining initial larger source particles. The more widely used method is described below.

For the examination of the stormwater sediments, the maintenance of the natural state of the sediment was as important as it was for the particle size analysis. The majority of the samples analysed were collected in stormwater, either by the automatic sampler during storms or by hand from surface or drain flow. Sodium azide was added to all stormwater samples on their collection after preliminary examination, by both the Coulter Counter and the scanning electron microscope, had shown the treatment had no effect on the state of the sediment but, rather, prevented its deterioration, as described in Chapter 4. The samples were given no further treatment but, with a minimum of delay, were shaken and poured on to the filter in the method described in Section 4.2 after Lloyd, Stenhouse and Buxton (circa 1973). The filter was secured in a millipore 45mm diameter filter funnel and operated under vacuum. The quantity of stormwater poured onto the filter depended on the concentration of the sediment in the sample. For the majority of storms approximately 10ml was sufficient to provide a particle density on the filter such that aggregates and individual particles lay seperately and could be recognised individually but close enough together to permit rapid location of particles without time consuming tracking across the sample under the microscope. In addition the density had to be low enough for each particle to make a good contact with the filter to avoid electrical charging from non-conductance, under the electron microscope. The particle distribution on the filters was examined carefully to ensure the filtering process had not caused aggregation, either by the increased particle concentration as the water was removed, nor by the enforced congregation of particles created by the arrangement of the apertures on the filter plate. However it appeared from the photomicrographs that neither caused any artificial effects providing the particle density was correct as described above.

Millipore (0.45μm) and nucleopore (0.45μm) filters were used in procedure trials. Nucleopore filters were the more flimsy of the two and as a result the more rigid millipore filters were easier to use in filtering. The filters were dried at room temperature on clean aluminium foil. The millipore filters tended to stick to the foil during drying and easily broke up in attemps to release them. Nucleopore filters caused no such problems. The electrostatic curling reported by Le Guen, Rooker and Vaughan (1980) was only found to occur when the filter remained exceptionally wet after filtration as a result of too great a density of sediment. In this event the sample was too dense for electron microscope examination anyway, and a further aliquot was filtered. Occasionally some slightly wetter filters curled a little on drying but these usually flattened out again with no detrimental effect to the sediment.

6.6.3. <u>Sample Mounting</u>.

Krinsley and co-workers had studied sediment under the transmission electron microscope before the scanning electron microscope became available. Their early sample procedures for the scanning microscope (Krinsley and Margolis, 1969) evolved from the earlier transmission sample preparation methods (Krinsley and Takahashi, 1964). Krinsley and Margolis (1969) removed grains from replicas to be mounted on stubs. The entire replica was used by Soutendam (1967), for both light and scanning microscope analysis, having been silver coated although the light microscopy required incident illumination to overcome the transparency of the quartz.

Tovey and Wong (1973) in their examination of soils used conventional thin sections in which the pore fluid bad been replaced by resin and a fresh surface created by fracturing or peeling off a layer. The main aim of their preparation was to maintain the sample structure. Similarly, Baynes and Dearman (1978) required the preservation of their soil or rock specimens. However their method of grinding down, or fracturing, the rock surface, taking a peel and removing the grinding marks by chemical etching, would appear to involve artificial abrasion and the destruction of soil structure.

Jenkins (1981) felt the preparation methods for optical and scanning microscope use were incompatable. He too, favoured the standard thin section technique which he used with oil immersion for optical microscopy but used the same section for the scanning microscopy after the removal of resin by low temperature ashing. Indeed he stressed the importance of optical micrographs at a range of magnifications for the relocation of the sample with the scanning microscope.

Whether the scanning electron microscope sample comprises loose grains, a piece of filter, or thin section, it must be securely attached to the stub, making a good contact for electrical conductance away from the sample. Krinsley and Margolis (1969) attached the sample to the stub using duco cement, Tovey and Wong (1973) used araldite for their thin section samples, Baynes and Dearman (1978) used double sided sticky tape and for individual grains, Krinsley (1978) used Elmers epoxy resin. All these methods are accepted but it is important to know the background count produced by the method in use for its comparison with the sample spectra.

A spot of silver dag is used to ensure electrical conductance away from the non-conducting sample and stub. Only a small amount is needed and, providing it is in contact with both the sample and the stub, its position is unimportant. Tovey and Wong (1973) covered the whole sample apart from that under examination, Baynes and Dearman described dagging the entire edge while Le Guen, Rooker and Vaughan used the silver dag to adhere the sample to the stub. However these methods are unnecessary, particularly in the light of the high cost of the silver dag.

It was important that the background elemental count of the filter used for stormwater sediments should be known and subtracted from the sediment spectra for time results. The millipore and nucleopore filters had negligible counts but the latter was preferred for the reasons described above. A selected portion of the filter was affixed to the carbon stub with double sided sticky tape which also showed negligible background counts. Again, to avoid background counts a carbon rather than an aluminium stub was used.

6.6.4. Sample Coating.

Once mounted, the sample must be thoroughly coated by a conductor, commonly carbon or gold. Carbon has the advantage of not registering peaks on the energy dispersive x-ray analysis spectra while gold produces three dominant peaks with the possibility of obliterating smaller but required elemental signals. Carbon coating employing the evaporation of carbon electrodes under vacuum is a lengthy but efficient coating technique. Tovey and Wong (1973) reported that carbon was also more suitable for samples with voids than gold. They, like Baynes and Dearman (1978) and many other authors, coated first in carbon and then in gold to gain the advantages both of a thorough coating and of the superior conductance of the gold. In addition, it was found that often gold did not stick well to the samples without first coating with carbon. The effects of charging from incomplete coating obscure from view those areas of the sample effected. Charging may occur as bright patches, broad black bands and distortions of the field of view, as was found during the present study and described by Baynes and Dearman (1978). Samples were coated, during rotation, directly from above (Krinsley and Margolis, (1969) but a better result was achieved from coating at two positions of tilt during rotation (Tankard and Krinsley, 1975). The method employed depends upon the degree of roughness of the sample and must ensure voids and areas overhung are coated.

Carbon coating gave good results for elemental analysis of the stormwater sediment with little or no charging. However once the elemental composition of the stormwater sediments had been established a gold sputter coater was used in preference for its rapidity and high resolution results under the microscope where it emits more secondary electrons than carbon. Coating by this method was found to be very thorough and charging only resulted from incomplete coating on exceptional particles of greater than 100μm. This was the case with the hand-collected samples where the increased relief created voids and shadowed areas. Recoating from a different angle usually coated these areas successfully.

6.7. The Preparation of Samples for Dual Optical and Electron Microscope Examination.

Initially the sediment analysis program included the routine transfer of samples from optical to electron microscopes to record photographically for the same sediment, the different parameters produced by each method.

The sediment sample was collected on a filter and dried as described above. Under the binocular microscope a small area containing at least 100 particles was encircled and a cross marked to aid the relocation and orientation of the particles from one microscope to the other. Millipore filters permitted the use of fine glass needles although extreme care was necessary to avoid tearing. The result left the particles unaffected but was difficult to view with the naked eye. A fine nibbed biro was more effective on nucleopore filters although, being relatively large, it devastated the particles in its path and had to form a larger circle to leave the central particles untouched. The advantage of being seen made this method useful in the remainder of the preparation and the problems got over in the light of the considerable advantages of nucleopore over millipore filters already mentioned.

A piece of fine plastic film was laid smoothly over a glass slide and the encircled section of the filter laid on top. Two drops of *Filter Count were placed on the filter rendering it almost transparent without apparently affecting the particles. The film and Filter Count were monitored elementally since some films produced a strong chlorine peak. The film chosen largely comprised vinylidene dichloride with polyuryl chloride and a crylonitrile added to provide flexibility. The spectrum contained signals for chlorine and sulphur but as both were less than 1% of the particle spectrum they were considered to be negligible.

The sample thus prepared was viewed with incident light under the binocular microscope where colour and relief could be examined. Although the aim of the preparation was to permit subsequent electron microscope examination, fresh particles straight on a filter were much clearer to view. The sample was also examined with transmitted light under the polarising microscope. An attempt was made to determine the minerals present by their birefringence and extinction angles but this proved unsuccessful as a result of the multi-faceted minerals which were severely engrained with impurities. In addition, the remnants of the filter reduced the amount of light reaching the particles. For satisfactory results stringent particle cleaning was necessary but the process would probably have damaged the surface features under examination.

For scanning electron microscope examination the plastic film was peeled off the glass slide and fastened onto a stub with double sided tape. The remaining filter and film were trimmed off and the sample Jagged and carbon coated as described above.

The technique, as described above and in Hamilton, Roberts and Ellis (1981) was shown to be sound in trials with sediment greater than 100μm. However, the resolving power of the photographic equipment of the binocular system was insufficient to photograph the stormwater sediment in the range of 1 to 40μm at magnifications greater than 40 times. At that magnification

*Supplied by Packard Instrument Co. Illinois USA.

there was insufficient detail available to be useful. As a result, rather than the hoped for overlap of magnification and comparison of optical and election micrographs there was a gap in the magnifications available and the method was only useful in isolated samples of large particles.

6.8. The Principle and Mode of Operation of the Scanning Electron Microscope.

6.8.1. Electron Emission and Elemental Analysis.

Chandler (1980) set out clearly the four forms of electron emission monitored by the scanning electron microscope and explained how each provided a different type of sample analysis: x-ray microanalysis, cathodoluminescence, energy loss spectrometry, and auger electron spectrometry, of which only the first was used in the analysis of stormwater particles.

High energy incident electrons replacing lower energy orbital electrons emit the excess energy as an x-ray which is characteristic of the emitting atom. The element is identified by a detector: either a wavelength dispersive crystal spectrometer or, more commonly an energy dispersive solid state detector. Many elements may be irradiated simultaneously producing a spectrum indicating their relative proportions. Incident electrons may also interact with the nucleus; being attracted to it they lose energy on deceleration which is emitted as a continuous spectrum specific to the element.

6.8.2. Scanning Electron Microscope. Mode of Operation for Stormwater Sediment Analysis.

The microscope employed in this study was a new model of the ISI stereo-scanning microscope.

Up until now the scanning electron microscope has been most commonly used in the secondary-electron mode. Page (1980), in his paper on the future of the scanning electron microscope, described the tendency of users to treat the instrument simply as a strong microscope by concentrating on this mode. The present study is guilty of this although mainly because of the need to concentrate on quantifying the results.

The secondary electron mode provided a clear view of the particles and the surface features in a three dimensional fashion. The accelerating voltage varied from 7 to 15kv depending upon the magnification; the working distance was 23mm and the tilt 30°, dynamic focussing compensated for the tilt.

Samples were first located at a low magnification of 80 or 90 times. A very good idea of the dominant type of sediment in the sample was gained by preliminary tracking across the stub. Aggregates were predominately viewed and photographed in the region of 5000 to 15000 times while individual particles of 1 to 5μm were examined at around 20 to 40000 times and specific features were examined at anything up to 80000 times but predominantly around 50000 times. An overall view of the particle distribution was gained at 1 to 2000 times and from that a random selection of particles made for detailed examination. Particles were examined in up to ten evenly spaced areas of the field of view and were marked for reference on an instant polaroid print or low magnification view field in the microscope memory.

From each point further particles were selected at random by tracking a fixed interval to left, right, above and below the previous position. 35mm film was used for reasons of cost; the wave form line was used for the camera focussing.

The number of particles considered representative is a controversal topic among authors. Many of the authors, particularly the early ones did not mention the number of grains studied and many refer to them in percentage terms only. Pittman's (1972) results were from an unspecified 'large number of grains', Douglas and Platt (1977) examined 25, Bull (1978a)

50, Wilson (1978) 10 per size fraction, Higgs (1979) 20 per sample area and Middleton and Davis (1979) 21 sand samples from 10 sand bars at a total of 1068 grains. In most cases where the author stated the number of grains he justified that number; the lower figures of 20 to 50 were considered to cover the range of features and the larger figures as being statistically viable. Krinsley and McCoy (1977) considered there was a wealth of environmental evidence on a few grains which are not necessarily a statistically significant number. Baynes and Dearman (1978) considered, rather the quantity of features and felt that althouth the 1cm^2 surface of a scanning electron microscope sample is not likely to be representative of huge rock outcrops such features can at least be related to the weathering intensity along a gradation observed on a field scale. Bull (1978b) gave the problem some attention and found the analysis of more than 20 grains impracticle and that 15 to 20 were sufficient to demonstrate the environmental features. It would seem to depend on the environment since some produce a greater variety of features than others. From the stormwater sediment studies and considering the long length of time necessary to thoroughly examine surface features 20 to 50 grains seems acceptable and it is questionable that the results of over 1000 grains are sufficiently detailed to be useful without having been the subject of long research.

During the research on the stormwater sediments each sample represented one point in a storm, one position along a drain or one land use type around the catchment and approximately 10 particles were studied for each sample. More than that was prohibited by the time and high cost of examination. Within these constraints at least 10 photographs were taken per sample and more often 15. The quantitative analysis required photomicrographs of whole particles but the form of entire aggregates and the detail of specific features was also of interest. As a result photographs were fully analysed for each sample. Considering the care taken in selecting random yet representative particles, this number is considered adequate to clearly define the nature of the sediment and to classify it according to its original environment.

6.9. Photographic Analysis.

6.9.1. The Measurements of Features from Photomicrographs.

The measurement method recommended by Krinsley and McCoy (1978) for electron micrographs, was firstly by the comparison of features with sized plastic spheres on the grain surfaces. The method compensates for any apparent shortening of curved surfaces on the photomicrographs. Secondly, the authors suggested the use of stereopairs after Smith (1977). Tovey (1978b) took up the latter method and stated the need for tilting and mathematical compensation, for the loss of true dimensions towards the edges of the photomicrographs. Stereographic methods, largely adapted from photogrammetry, have proved unsuitable for accurate spatial quantification of the micro-features. Tovey (1978b) suggested some automation of the procedure, perhaps incorporating the development of the computer interfaced with the microscope, would make the stereo technique viable.

Although Krinsley (1978) and Tovey (1978b) have attempted the quantification of surface features, no straightforward method has resulted. In an effort to make some headway the stormwater sediment features have been measured and classified as a percentage area of the total particle area, as described in detail below. The method appears to minimise edge distortion effects, particularly when a particle occupies only the central portion of the photomicrograph.

6.9.2. The Analysis of Stormwater Sediment Textures.

The method of quantitative surface texture analysis of stormwater sediment was developed from the work of Bull (1978b). Bull (1978b) drew up a list of twenty two grain surface features based on the descriptions by Krinsley and Doornkamp (1973). Bull (1978b) compiled presence and absence data of the features for each grain and carried out cluster analysis (Ward 1963) and linear and multiple discriminant analysis. He was able to relate the results to the different grain origins.

Similarly all the features were listed to fully describe the stormwater sediments. Not all the features described by Bull (1978b), and Krinsley and Doornkamp (1973) were appropriate and some additional features, resulting from the urban origins and processes, were added. The features were listed according to the process of formation in Table 7.1. After preliminary trials of the presence or absence procedure (Bull, 1978b) on the stormwater sediments, the method of quantifying the area of each feature present was developed.

The method devised was as follows. A transparent graph paper overlay was placed over the photograph and the particle or aggregate outlined. The total number of millimetre squares encompassed was counted and equated to 100%. The area of each feature on the grain surface was traced onto the overlay until the whole area had been accounted for. The area, in millimetre squares of each feature was calculated as the percent of the total area Appendix 5. Having established the detailed distribution of features, the majority of samples were analysed more rapidly by the Fuzzy Classification Technique (Chapter 3). The mean and percentage results of this data were then analysed and particle suites were established for each type of sample.

CHAPTER 7.

SEDIMENT SURFACE TEXTURES AND PROCESSES OF THEIR ALTERATION.

7.1. Introduction.

The features of surface textures, studied with the scanning electron microscope as shown in Chapter 6, are described here in the context of their occurrence as suites of features determined by the parent material and mode of transport.

The Fuzzy Theory technique using an abbreviated summary selection of features was used for the bulk of the sediment micrograph analysis. This approach was found to be more appropriate to the examination of a large number of samples and sufficiently sensitive to reveal the differences between samples. In this way sediment surface textures are related to their catchment land uses and to their progressive alteration during transport through the drainage system. In addition, the method is used in the following chapter to describe the variations in sediment through storms of different types.

Where possible, feature definitions are adopted which have been standardised in the literature. Most of the stormwater sediment studied here is from roadstone which is of geological origin and hence many of the surface textures apply which have been described in the literature on quartz sand grains, principally by Krinsley and co-workers and in particular from the specific definitions given by Krinsley and Doornkamp (1973). However, the processes of abrasion in roadstone construction, subsequent vehicular erosion and stormwater transport vary from the natural ones acting on quartz sand grains documented in the literature. The original parent material features may be obliterated or altered in distribution and degree which can lead to problems in feature definition. Where standard features (according to Krinsley and Doornkamp, 1973) can be recognised the stormwater features are labelled accordingly and mention is made of variations and the probable processes which caused them.

The textural features of stormwater sediment from other sources are described in a similar manner. The particles constitute only a small proportion of the sediment sampled but are very varied and not always easy to define. Their sources probably include building fabric, eroded vehicle fragments, industrial output especially flyash, also chemicals, detergents and plant debris, particularly pollen grains. In some cases EDXA results, where available, combined with comparative studies with the literature help define particles, but again processes of manufacture and transportation, which are rarely fully known create unexplained features and feature alterations.

Finally, some aspects of the sediment, notably the aggregated form, seem to be solely a response to the urban storm sewer system and are therefore described and defined according to the features and processes observed in this catchment study.

7.2. Texture Surface Area Analysis.

7.2.1. The Compilation of the Feature List.

The comprehensive list of features shown in Table 7.1. describes the surfaces of particles from sources in the catchment, and after surface and drain stormwater transport. The initial detailed area analysis of particle surfaces meant describing every feature and accounting for the entire surface area of the particles visible in the micrographs. Many features had been described in the literature and were identifiable on the stormwater sediments. The majority of the abrasion features listed by Bull (1978b) are adopted here as well as appropriate features of quartz sand grain surfaces described by Krinsley and Doornkamp (1973). Because the relevant literature is concentrated on naturally occurring rock fragments and especially sand grains, not all the features seen on urban sediments were accounted for. Descriptions of these features were devised specifically for this study for example, particle aggregation and the forms of surface precipitation and solution. Lastly, considerable reference has been make to McCrone (1973-1980) for non-mineral and crystallographic substances frequently occurring in urban environments such as flyash, paint and decayed metal fragments.

7.2.2. Texture Analysis Method.

Particles were examined from the four major sources of sediment in the catchment; roads, buildings, air and the stormwater

TABLE 7.1.

PARTICLE SURFACE FEATURES

Precipitation and Overgrowth Features.

1. Complete, thin (<0.5μm), smooth coat.
2. Crystallographic overgrowths.
3. Other, less distinguishable coat.
4. Frosting - fine silica precipitation in small discrete granular form.
5. Silica plastering - angular grains adhering to fresh face of particle, a result of impact.

Solution Hollows.

6. Rounded hollows <0.1μm diameter and depth.
7. Rounded hollows >0.1μm diameter and depth.
8. Precipitation surface attacked by solution, hollows <0.5μm diameter and depth.
9. Precipitation surface attacked by solution, hollows >0.5μm diameter and depth.

Abrasion Features.

10. Fresh featureless face.
11. Straight steps.
12. Conchoidal steps.
13. Straight striations.
14. Curved striations.
15. Angular impact hollows.
16. 'V' notches.
17. Pitted surface.
18. Cleavage breaks, of fibrous asbestos type or other.
19. Crinkly appearance of clay cleavage.
20. Feldspars, with parallel twinning.
21. Cracks.

Features Above General Level of Particle Surface.

22. "Upturned plates" on spherical flyash particles.
23. Ridges.
24. Adhering particles.

Surface Relief (regardless of feature)

25. 0.0- 0.09 µm
26. 0.10- 0.24
27. 0.25 - 0.49
28. 0.50- 0.74
29. 0.75 - 0.99
30. 1.0-1.25 µm

Shape.

31. Angular.
32. Rounded
33. Spherical
34. Subangular
35. Subrounded
36. Small scale jagged outline.

Mode.

37. Individual particle.
38. Individual particle in loose cluster of several particles.
39. Cemented cluster of particles.
40. Irregular sulphurous background of airborne sediment.

Size.

41.
1. <0.5 µm
2. 0.5 - 0.99
3. 1.0 - 4.99
4. 5.0 - 9.99
5. 10 - 14
6. 15 - 19
7. 20 - 24
8. 25 - 29
9. 30 - 34
10. 35 - 39
11. 40 - 50
12. 50 - 60
13. >60 µm

runoff. Table 7.2. shows the number of particles from each origin exhibiting each feature. From Table 7.2. it can be seen that a number of features are common to all sources; others are unique to, and therefore diagnostic of, one origin; and the remainder are common to two or three sources. The features which all sources have in common are largely the results of abrasion during transport in the air and water, which produces subangular and subrounded shapes of all sizes. Some fresh-faced angular material occurred in all sources whether the sediment was newly eroded or had undergone abrasion previously. In road, roof and stormwater samples this sediment is predominantly from the erosion of road and building materials, but of the airborne sediment some is more likely to be the product of combustion, for example, flyash.

The features which are unique to sediment from each source distinguish it from sediment from the other sources in the catchment. The unique and diagnostic feature of the road sediment is the presence of feldspar crystals which are found in the granitic roadstone. The feldspars appear to be weathered during erosion and runoff and do not arrive at the outfall so are confined to road sediment samples. The feature is not widespread and although diagnostic where it occurs, it is the unique combination or suite of features which in this case fully describes the sediment and distinguishes it from other sediment types. The suite includes angular and fresh-faced particles

TABLE 7.2.

PARTICLE AREA-TEXTURE ANALYSIS.

PERCENTAGE OF PARTICLES PRESENT EXHIBITING SURFACE FEATURES.

Feature Number (as in Table 7.1)		Storm Sediment		Road	Roof		Air	
1	ii	0		0	0		2	ii
2	i	55	i	50	20	i	4	ii
3		0		0	0		0	
4	ii	57	ii	0	0		0	
5		0		20	0		2	
6	ii	32	ii	0	0		0	
7	i	12	i	10	10	i	2	i
8	ii	7	ii	0	0		0	
9	i	10	i	40	20	i	4	i
10	i	71		40	40	i	11	i
11	i	41	i	30	20	i	4	i
12	i	36	i	30	20	i	4	i
13		9		10	0		0	
14		9		10	0		0	
15	i	85	i	60	20	i	4	i
16	ii	12	ii	0	0		0	
17		20		10	20		0	
18	i	43	i	30	20	i	2	i
19	ii	0		0	20	ii	0	
20	ii	0		10	0		0	
21		19		0	30		0	
22		2		0	30		81	
23		2		0	50		0	
24	i	83	i	60	30	i	51	i
25-30	i	40	i	10	10	i	64	i
31	i	36	i	50	10	i	4	i
32	i	9		0	0		4	
33		0		0	30		79	
34		62	i	20	40	i	2	i
35		38	i	50	20	i	4	i
36	i	20	i	20	40	i	4	i
37	i	38	i	90	90	i	13	i
38		12		0	0		77	
39	ii	45	ii	0	0		0	
40	ii			0	0		89	ii
41								

i = features common to all sources.

ii = diagnostic features, unique to individual sources.

which are particularly distinctive; they are well-developed, clearly recognisable and make up the majority of the features present. The sulphurous background of the air samples is a diagnostic feature. It occurs in all the samples and thus distinguishes them from any others but is not regarded as a constituent of runoff sediment. Spherical particles are diagnostic of airborne sediment but strictly cannot be classed as such unless several occur in the same sample. This is because occasionally individuals are found in other areas where they have been transported through the system in runoff. The unique features of both roof and stormwater sediments describe a high proportion of the sediment as well as being diagnostic. The "crinkly" appearance of much of the roof sediment is derived from the weathering of building materials and is only recognised in roof samples. The unique features of the stormwater sediment derive from the drain flow transport and largely from silica activity which creates frosting, precipitation growth and interparticle cementation. In addition 'V' notches occur during abrasion within the drain.

Where features are common to two or three sources the explanation largely depends on the survival rate of those features through the system. For example, road material survives runoff and stormwater transport so is sampled both on the road and at the outfall whereas of roof and airborne sediment only the spherical particles are sampled elsewhere. Pitted surfaces appear to be a chemical or physical feature of wet environments so are found everywhere except on airborne sediment. Plastering is associated with outstandingly fresh-faced angular particles and as such occurs only on airborne and road particles although the formation of the features in each case may not be related.

The results of the analysis are diagnostic suites of features which fully describe, and distinguish between, the sediment generated from all the catchment sources.

7.3. The Fuzzy Technique.

7.3.1. The Fuzzy Theory.

Fuzzy techniques of analysis provide a method of simplifying, and recognising patterns in any variables which are too complex for a precise solution. This may be necessary because the number of variables is too great and their interrelationships too intricate, or because the variables do not naturally have numerical values allowing standard mathematical procedures (Zadeh, 1965, 1975). Both of these and especially the last, apply in the present case.

The structure of the Fuzzy technique provides limits to the range of values assigned to a variable but permits values to be allotted to such relative variables as for example small, medium and large, or to absolute variables such as colour, or the impact features in the case of the stormwater particles. The combination of values for all the variables present (the surface features in this case), describes the subject (the particle or sample of particles), and allows the comparison of it with another. The values given to the variables may be plotted and thus produce a curve for each subject which again is easily comparable with that of another. Further details of the Fuzzy Theory are given in Appendix 4.

7.3.2. The Application of The Fuzzy Technique.

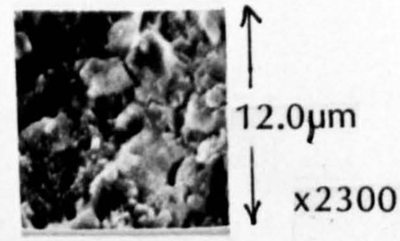
To optimise the application of the Fuzzy Technique over that of the detailed area analysis the list of features had to be condensed to maintain accuracy of results with minimum loss of detail. The shortened list is shown in Table 7.3. and is made up of combinations of features from the full list (Table 7.1.). The features of stormflow alteration are mainly the result of silica precipitation and solution and are largely obtained from observations of stormwater particles made in this study. These categories combine sediment form (individual or aggregated grains) and coatings, which occur together on the particle but each feature was described separately in the full list. Pitting appeared to be more frequent after sewer transport so is included here although whether it is a chemical or a physical process is, so far, undecided. In the section on abrasion features in Table 7.3. the features which almost always occur together have again been combined and thus the detail and accuracy of the classification remain undiminished. The list of clay minerals and airborne sediment features remains much the same as in the full list. Spherical shape and the upturned

TABLE 7.3.

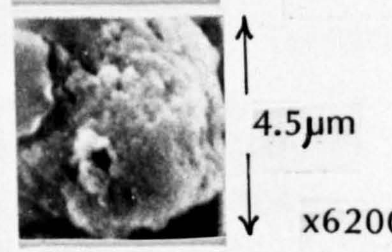
SUMMARY FEATURE LIST FOR FUZZY ANALYSIS

Features of Stormflow Alteration

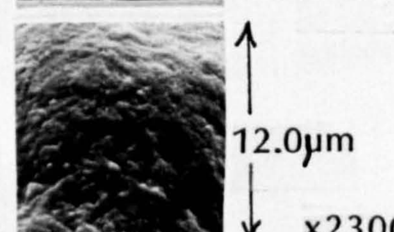
A Aggregates and frosting (4,37,38,39)



B Silica overgrowths and precipitation solution surface (1,2,3,5,24)

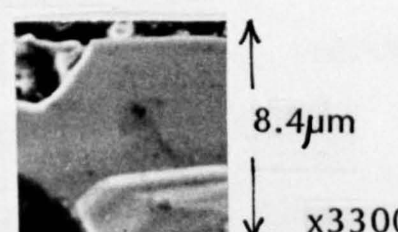


C Pitted surface (6,7,8,9,17)

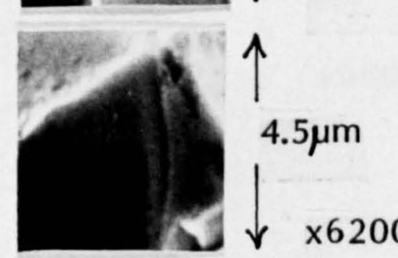


Abrasion Features Most Commonly on Fresh Particles

D High percentage fresh featureless face (10)



E High degree of angularity (31,32,34,45,36)

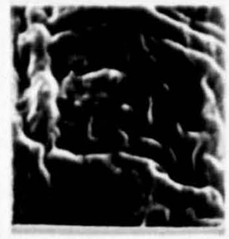


F Steps (11,12,13,14)

G Impact features and 'V' notches (15,16)

Properties of Clays from Building Materials

H Crinklyness (19)



4.6µm x6100

I Clay cleavage (18)

8.4µm x3300

Features of Airborne Sediment

J Sphericals (22, 33)

3.2µm x8700

K Sulphurous background (40)

5.0µm x5600

(Numbers represent equivalent single or combined features from full detailed list in Table 7.1.)

plate surface have been combined as they appear to be inseparable features of spherical silicon-based particles and flyash, and absent from other sediment studied here. Almost all the features on the original list (Table 7.1.) are needed to account fully for the total particle areas. They have been combined where they have been observed occurring together as suites of features, as is shown in Table 7.3.

The natural occurrence of the features in suites distinctive of their sediment origins meant that the data lent themselves to this procedure very well and the rapidity of the method was far more suitable for the examination of a large number of samples than either the method outlined by Bull (1978b) or the detailed area analysis. For all the particles examined each feature present was allotted a value on the scale 1 to 5. Less than five classes provided insufficient detail and more than five was unnecessarily complicated. The value given depended both upon the area covered by that feature and on its degree of development. For example, where features such as precipitation and solution surfaces or upturned plate surfaces completely covered the particle a value of 5 would be given. Alternatively, where impact features covered only a small area of the particle a high degree of development would warrant a high score.

The Fuzzy scores were summarised by the average value for each feature and the percentage of particles present with that feature. The average value gives a good indication of the extent and degree of development of the feature. Importance is also attached to the proportion of particles exhibiting each feature. The recurrence of particles exhibiting features with the same percentage values indicates those features are of a suite. High percentages show the dominance of such particles in the sample and thus the dominant contributory source of sediment. Mutually exclusive features however point to the sediment in the sample coming from more than one source. The results of these analyses provide full details of the sediment sampled around the catchment and along the drain and are described in the following section.

7.4. Sediment Characteristics from the Four Major Origins.

7.4.1. Road Sediment.

The four main categories of sediment were analysed by the detailed surface area method and the results are given in Appendix 5.

Road sediment is largely the result of the erosion of granitic or lime-stone roadstone by vehicles and weathering, and its collection and removal to the roadside gutters in stormwater runoff. The generation of road sediment from the road surface is described in reports from the Transport and Road Research Laboratory on alterations in the road surface caused by traffic and weatherimg. A number of road surface materials were studied of which the results from quartzite and gritstone are the most applicable to this study (Neville, 1974). The road surface is considered to have two scales of roughness, from 10μm to 50μm and from 1μm to 5μm. During the winter weathering is severe, particularly the physical break up of the surface by frost, and by the action of dissolved carbon dioxide in rainwater and sulphur dioxide in the atmosphere. Fine fragments eroded off the road surface add to the detritus on the road and under vehicle tyres. This increases the abrasive action by traffic and accelerates the loosening of other weaker mineral grains. The detritus is washed away in runoff which carries the sediment off the road to the gutters and drains. The surface is cleared first and the crevices or finer scale surface cleared later (Gutt and Nixon, 1972). The efficiency of the scouring by the runoff depends on the intensity of the rainfall, as described in Chapter 8. During the summer months the roads are drier and the effects of weathering less severe. The detritus is ground into increasingly fine material which "polishes" the surface (Neville, 1974). Quartz is very resistant to polishing but minerals susceptible to weathering, for example feldspar, are eroded, add to the detritus and act as an abrasive polishing agent together with fillers used in tyres.

The road sediment collected in the catchment comprises alumino-silicates of which quartz grains predominantly reach the outfall. The quartz grain surface features are very similar to the quartz sand grain abrasion features described by Krinsley and Doornkamp (1973) and summarised in their index

Table. Road sediment occurs as individual particles, fresh-faced with plain surfaces and angular in outline, and covers the entire size range of $1\mu m$ to $40\mu m$ (S.E.M. data, Appendix 5. and Particle Size data, Chapter 5). Predominantly of quartz mineralogy, these particles are the most durable sediment sampled. Grain surface textures comprise clean mechanical breakage features caused by the abrasion processes of the saltating or suspended load, for example straight and conchoidal steps (Plates 1, 2, 5) diagnostic striations, impact blocks removed from the surface on collision and occasional physically abraded 'V' notches. The 'V' notches are only moderately well-developed, and they do not occur in large numbers as described in the literature. This is possibly because in this system the abrasion is insufficiently stringent to cause continual erosion or alternatively because those that are visible are remnants of a previous transport cycle. In addition, pieces of plastered silica from very high energy impact collisions are found on fresh faces. Feldspars (Plate 9), with their distinctive form of cleavage, are also diagnostic of road sediment samples but being so easily weathered rarely survive stormwater transport.

Many road particles carry silica precipitation and solution features which indicates a period in rainwater collected on the road surface and in gutters (Plates 3-7). These features are in the early stages of development compared with those which have undergone sewer transport. Evidence of the complete, thin, silica coating of

ROAD SEDIMENT

Fresh-Faced Angular Particles.

Scale Bar

— 0.1 μm
— — 1 μm
— — — 10 μm
— — — — 100 μm

Plate 1 x 1400 Fresh-faced, angular particle with conchoidal steps.

Plate 2 x 3000 Abrasion features straight steps, striations and impact blocks; plastered fine particles.

Silica Precipitation and Solution Features Indicating Period in Runoff.

Plate 3 x 11000 Particle with silica precipitation and solution features overlying conchoidal fracture of angular particles.

Plate 4 x 13300 Subangular particle with silica precipitation—solution surface irregular background of millipore filter.

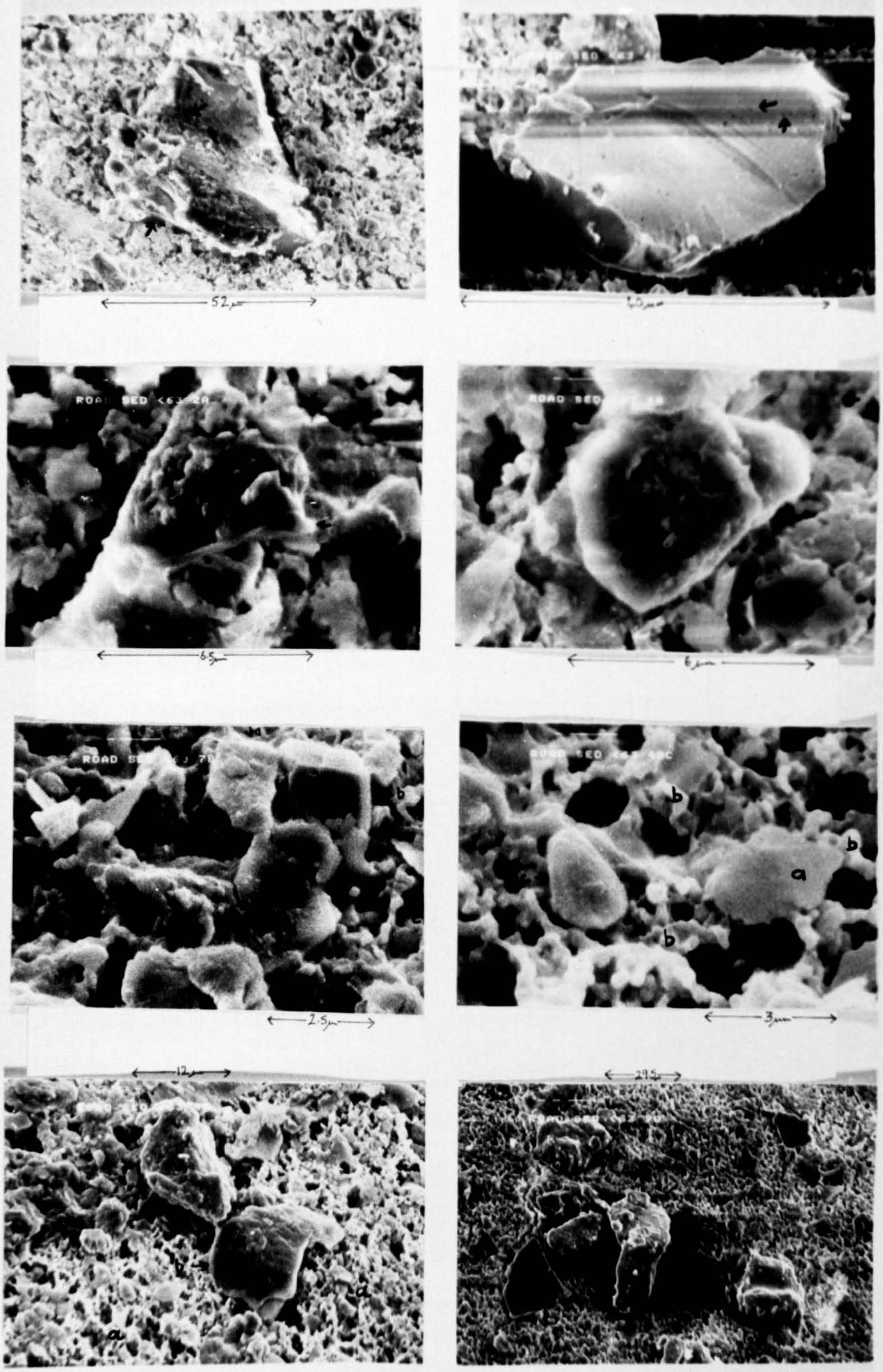
Plate 5 x 12000 Subangular particle with early silica precipitation (a); angular blocky particle with straight step and impact features (b); millipore filter (c); subangular relatively fresh-faced particles with adhering fragments (d).

Plate 6 x 14600 Small angular fresh-faced particle (a); millipore filter (b); subangular particle with early silica precipitation (c).

Plate 7 x 2700 Millipore filter (a); widespread particle coverage of silica precipitation and solution features (b).

Silica Coating.

Plate 8 x 880 Silica coated particles with adhering particles and possibly isolated silica precipitation.


52µm
6.5µm
6µm
2.5µm
3µm
12µm
29.5

individual particles (Plates 8,9,10,) points to a stationary period probably during evaporation of surface water after rainfall. It is possible that these features are the results of, or enhanced by, the filtration and drying methods of the sampling procedure, but as they are neither universal within any one sample, nor found in every sample they are more likely to develop in the surface and drain water.

A smaller proportion of road sediment is generated by vehicle wear and tear. Particles of high iron content are attributed to rust and those of high titanium content (traced by EDXA, individual particles were not recognised) to road marking paint. However no clear relationship was found between the elemental composition of these particles and their surface textures.

7.4.2. Airborne Particles.

Airborne material is predominantly at the finer end of the size range, between 1μm and 15μm at maximum. Particles most frequently comprise silica and tend to be either spherical, of approximately 2μm diameter, or very angular. All airborne sediment samples have in common the diagnostic sulphurous background which is a continuous feature of irregular granular form (All plates). Airborne material has commonly been observed to be the most rounded form of sediment (Krinsley and

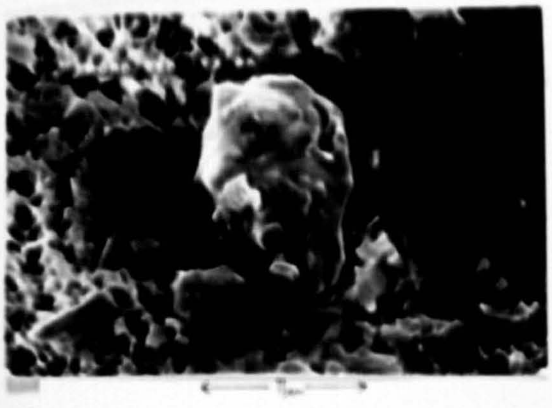
Plate 9 x 4000 Detail of almost complete silica coating, possibly of aggregate; fresh-faced angular fragments typical of roadstone erosion; feldspar (→).

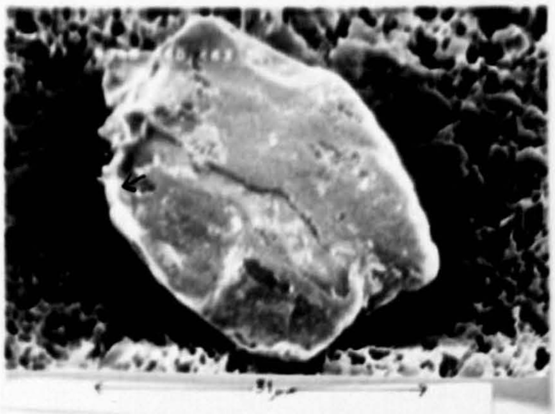
Plate 10 x 2900 Coating eroded on angular particle to reveal conchoidal steps (→); small subangular particles with silica precipitation.

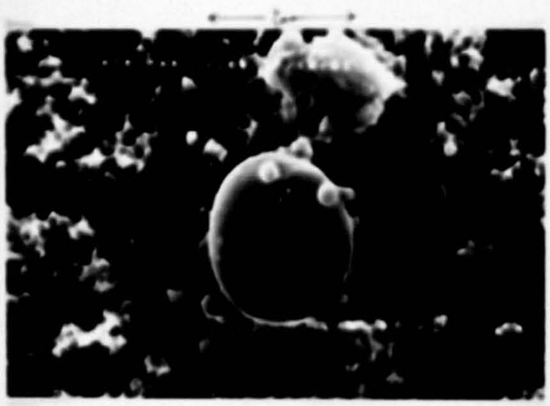
AIRBORNE SEDIMENT.

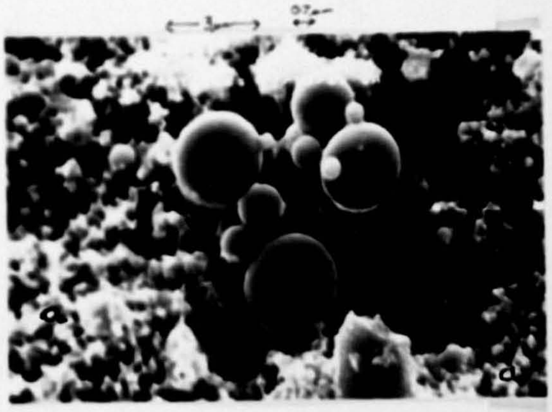
Plate 11 x 5700 Loosely clustered spherical particles (possibly flyash) with "upturned plate " surface; sulphurous background.

Plate 12 x 7300 Clustered spherical particles possibly due to electrostatic forces of particles or a result of filtering; irregular sulphurous background (a).









McCoy, 1978; Lindé and Mycielska-Dowgratto, 1980). The rounding of airborne desert sand grains is said to be caused by high energy impacts. While this is plausible in desert conditions of high sediment concentration, it is unlikely to have a widespread effect in this urban catchment. However the particles are considerably more rounded than in fluvial sediment where the water acts as a shock absorber against impact (Krinsley and Doornkamp, 1973). Many of the spherical particles closely resemble flyash, and in particular the coal flyash described by McCrone (1973-1980). The "glassy spheres" of flyash are composed predominantly of silicates (Gibbon, 1979; Mattigod, 1982) and comprise silica, aluminium, potassium, calcium, phosphorus, sulphur and iron in the case of the airborne sediment sampled in this catchment. X-ray diffraction spectra were available from the elemental analysis of this sediment but no quantitive measurements could be made.

There is no apparent relationship between elemental composition and surface texture. The textures are all low in relief at less than 1μm, and include shallow pitting and an irregular surface similar to the "upturned plates" described by Krinsley and Doornkamp (1973) although much of Krinsley's work is on larger spherical grains, for example, desert wind-blown quartz sand grains of 175μm to 355μm (Krinsley and Wellendorf, 1980). The proportions of the spherical particles which are predominantly silica and those which are flyash is uncertain without the extensive elemental examination of a large number of particles. The surfaces of quartz sand grains are recognised as "upturned plate" features but the term does not strictly apply to flyash surfaces in the literature. Whether or not the composition of the flyash is capable of developing upturned plates is unclear as it is intrinsically smooth. (Gibbon, 1979). However Lindé and Mycielska-Dowgla~~tt~~o (1980) have shown experimentally that "upturned plates" do develop by impact abrasions on quartz sand grains within 24 hours. As all the spherical particles appear to have similar surfaces whether they are quartz or flyash, this development remains a possibility as the result of the airborne impact collisions. The spherical particles are diagnostic of airborne sediment sampled in this catchment and occur either separately or occasionally in small, loosely adhering clusters (Plates 11, 12). This is possibly due to electrostatic charges on their surfaces (Keunen and Perdok, 1960; Nieter and Krinsley, 1976). The angular fresh-faced airborne sediment frequently exhibits firmly-adhering particles of silica or "silica plastering" (Plates 13, 14) (Krinsley and Doornkamp, 1973) where fragments appear to have collided sufficiently intensely for one or both surfaces to have melted, thus fusing the two together. Krinsley and Wellendorf (1980) calculated that in a 5μm feature of quartz (on a particle of 175μm to 355μm), the melting temperature would be exceeded in a collision at 15m/s. Whether or not conditions in the catchment or at the impact sampler could achieve anywhere near the required force for collision melting is unknown. It seems probable that silica plastering in this instance is more akin to the melting of material associated with industrial furnaces (McCrone,1973-1980)

Some further, less common features of airborne sediments are shown in Plates 17-23. Plate 15 (and possibly Plate 16) shows a type of exfoliation which was described by McCrone (1973-1980) as the result of gases trapped within the particle escaping and leaving a weakened surface vulnerable to abrasion. A particular example (Plate 15) also demonstrates the angular form with fresh faces which appears to have resulted from vigorous impacts on a spherical particle. A different form of flyash occasionally sampled in the catchment is shown in Plate 17. Although not spherical it is possibly flyash from flux (McCrone, 1973-1980). Strongly cleaved, fibrous particles, thought to be asbestos (McCrone, 1973-1980), occur solely in the airborne sediment probably because they are destroyed during subsequent transport in stormwater runoff.

At around 15µm the particles shown on Plates 18-21 are at the upper end of the airborne sediment size range and are considerably larger than the more typical particles so far described. They are similar in appearance to road and stormwater sediment in their degree of angularity and abrasion features and in particular what seem to be silica-precipitation and solution features. If this is the case it is suggested that such particles are entrained in the wind from surface sediment.

Plates 22 and 23 show distinctly angular particles, the former is similar in appearance to a clay particle and the latter possibly a metal such as magnesium (MacCrone 1973-1980), a product of combustion.

Plate 13 x 5000 Fresh-faced angular aeolian particle with silica plastering; sphericals (a); irregular sulphurous background (b).

Plate 14 x 3900 Angular particle with adhering angular individual particles; sulphur background (a) plain filter (b), filter aperture (c).

Plate 15 x 2700 Abraded spherical particle, upper exloliated surface (a), fine sphericals (b), sulphurous background (c).

Plate 16 x 15000 Irregular particle surface possibly rounded exfoliation surface on elongated spherical particle, perhaps a distortion effect of the microscope; a (→) spherical aperture in filter; b, sulphurous background.

Plate 17 x 3500 Combustion particle, possibly flyash from flux.

Plate 18 x 5700 Irregular quartz particle with small sphericals (a) and conchoidal step fracture (b).

Plate 19 x 3900 Irregular shaped particle with solution surface and adhering sulphurous material, also sphericals and adhering fine angular particles.

Plate 20 x 3300 Particle with apparent silica precipitation; early silica precipitation (a); small angular, fresh-faced particle with sulphurous deposits (b).

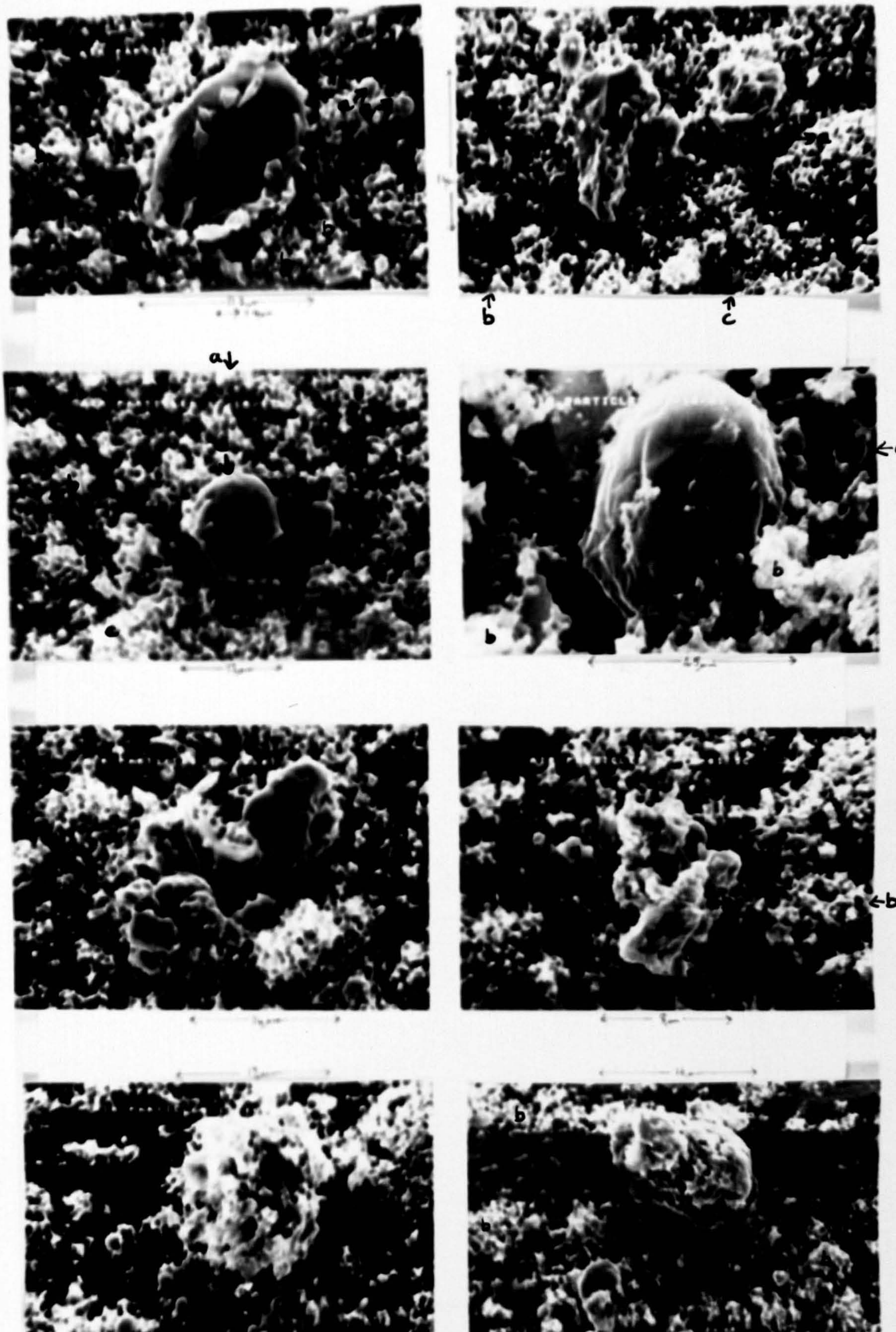
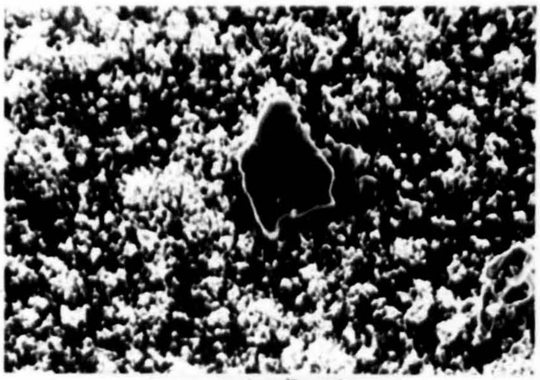

b
b
c
a
a
b
b
a
b
b
b
a

Plate 21 x 2600 Surface appearance of solution of silica precipitate; fine spherical particles.

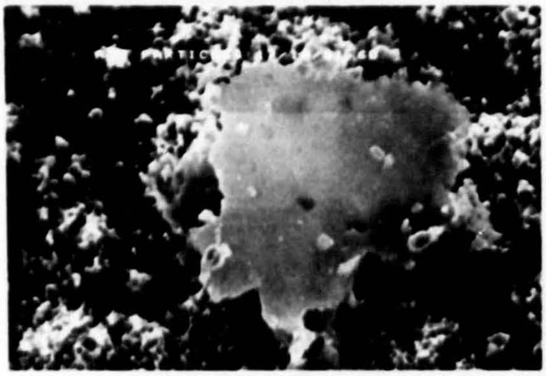
Plate 22 x 1500 Angular platy particle surface with finely abraded edge.

Plate 23 x 5000 Angular particle, flat surface with minor abrasions and a few adhering fine particles.

← 15 μm →



← 17 μ →



← 16 μm →

It is difficult to be sure about the causes of the features seen on these particles, especially the rare examples, merely from the comparison with micrographs in the literature without some knowledge of the particle history. The exact source of these particles especially is uncertain as they could have originated either from within the catchment or from some distance beyond. The explanations given here seem the most probable from the information available.

Only a little airborne sediment is found in roof samples, less on the roads and very occasionally is it collected at the outfall. The reasons for this appear to include its small size and low density allowing it to be easily transported away from the catchment on the wind. Airborne sediment washed out on to the surface is broken down by weathering and erosion and rarely survives the journey to the outfall. If it does survive, it forms a very small proportion of the sediment sampled there.

7.4.3. Roof Sediment.

The sediment washed off roofs is generally less distinctive than road or airborne particles. It is relatively fine sediment but the particles are slightly larger than the airborne samples at 1µm to 20µm. The sediment occurs as individual grains, sometimes with finer adhering particles. The sediment from eroded clay roofing tiles has a diagnostic irregular ridged pattern of low relief producing an irregularly ridged or "crinkly" appearance as shown in Plates 24-29. It is

Plate 24 x 3000 Overall view of roof sediment; spherical (a); "crinkly" particle (b), (c).

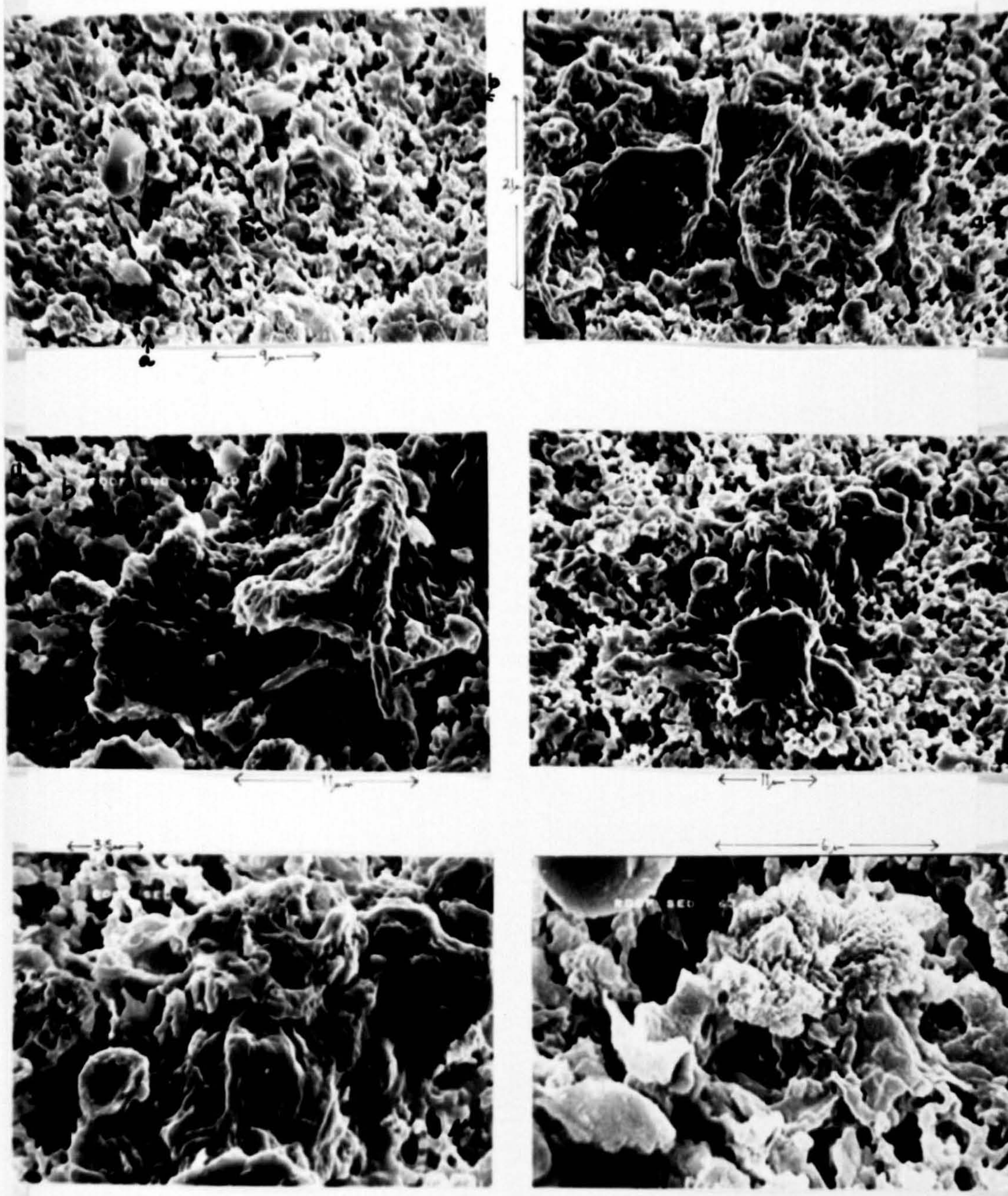
Plate 25 x 2570 "Crinkly" roof clay particle.

Plate 26 x 4700 "Crinkly" clay particle; irregular millipore filter (a), possibly piece of silica precipitation (b).

Plate 27 x 2600 "Crinkly" clay particle.

Plate 28 x 5700 Detail of Plate 27, crack in particle or in coating (a), millipore filter (b).

Plate 29 x 10200 Characteristic roof tile or brick clay.



assumed to be the cleavage fracture pattern of the tile clay. Plate 29 shows an irregular form commonly found on crinkly particles which may be either the result of solution of the clay particle or some surface precipitate. The exact definition is unclear.

Clays of flaky surface appearance, or "packets" of clay particles, similar to kaolinite (Tovey, 1978b; Waugh, 1970) also occur and are shown in Plates 30 and 31 but their jagged outline suggests some erosion of the natural form. Roof sediment also includes angular, fresh-faced particles smaller than those of road surface sediment. Some of these particles may also be further constituents of the roofing tiles while others were probably washed out of, or deposited from. airborne material (Plate 32). Samples taken directly from roof tiles and bricks are shown in Appendix 6. Flyash and other spherical particles are easily recognisable where they occur amongst roof sediment as can be seen in Plates 24 and 33.

There is some evidence of silica solution and precipitation which presumably occurs in moisture trapped in the guttering. However runoff is relatively effective and allows little time for slow flow and thus the overgrowths are only weakly developed like those shown in Plates 34 and 35.

Plate 30 x 14900 'Flaky' roof particle, possibly illite.

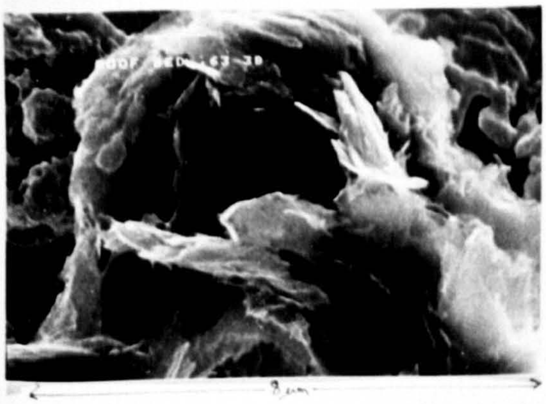
Plate 31 x 4400 Well cleaved particle or 'packet' of clay particles.

Plate 32 x 13700 Fresh-faced angular particle with adhering similar smaller particle.

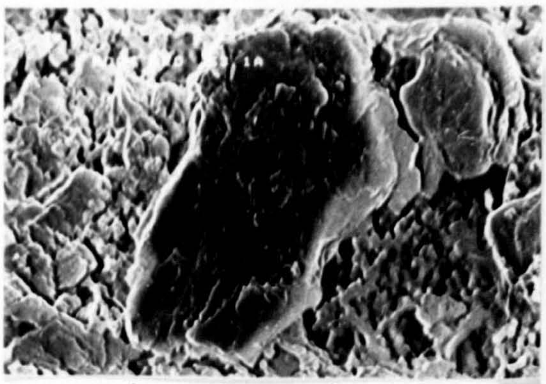
Plate 33 x 24700 Airborne spherical particle collected in roof runoff.

Plate 34 x 4700 Upper precipitation or plastered on surface, lower section possibly abraded; trapped airborne sphericals (→).

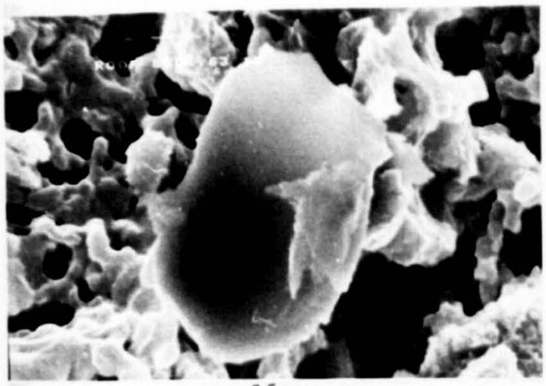
Plate 35 x 7900 Silica precipitation and solution on angular roof particle.



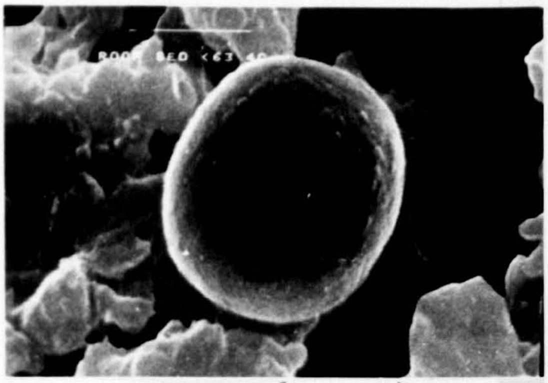
8μm



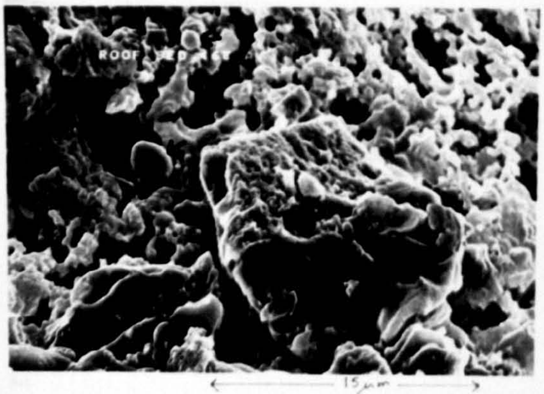
12μm



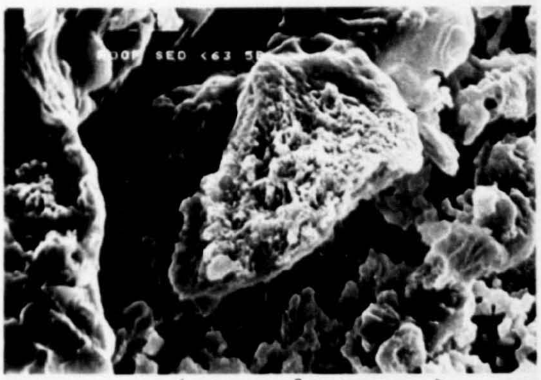
3.5μm



3μm



15μm



8μm

7.4.4. Stormwater Sediment.

The stormwater sediment is washed from roads, roofs and the air, by rainfall runoff into the sewer system and thence transported to the outfall. Diagnostic features of this sediment are those found on the sediment sampled at the outfall but they are absent or minimal on above-ground sediment. Therefore, it can be deduced that these features are the result of stormwater sewer transport. The road sediment is the most durable sediment collected above ground and thus best survives passage through the sewers. Due to the widespread network of roads and considerable and continual erosive pressures of vehicles it is undoubtedly also the sediment produced in the largest quantities in the catchment (also shown by Ellis, 1979 and Ellis and Harrop, 1984). As a result the sediment collected at the outfall is dominated by road sediment which occurs predominantly as silica cemented aggregates (Plates 36-70). The high concentrations of silica (discussed in Chapter 3) are shown here in the EDXA results (Plates 45-70). Aluminium is the second most dominant element present with varying amounts of magnesium, sulphur, chlorine, potassium, calcium, iron and occasionally titanium. In contrast, air and roof sediment rarely appear to survive the stormwater transport intact and recognisable particles of vegetation are seldom seen under the microscope (Chapter 3). A sample of that minority which do get through the system are given in Plates 71-81. The aggregates are diagnostic of stormwater sediment and account for the bulk of the sediment at the larger end of the size range. The silica precipitation and solution features may take the form of a coating with a low relief surface of

STORMWATER SEDIMENT

Silica Cemented Aggregates.

Plate 36 x 4800 Small aggregate in early stages of development with fresh-faced angular (road) particles being incorporated by cementation; some silica frosting.

Plate 37 x 2710 Fine angular and subangular particles aggregated by silica cement, frosting on aggregate and plain nucleopore filter (→).

Plate 38 x 2040 Aggregated angular and sub-angular particles with silica frosting.

Plate 39 x 1350 Well-developed aggregates with frosting visible over both sediment and filter; l.h.s. early open structure of aggregate, particles clustered and cemented.

Plate 40 x 1600 Mature aggregate, particles well-consolidated and firmly inter-cemented; additional individual particles being incorporated around perimeter; early precipitation on upper surface.

Plate 41 x 1600 Mature aggregate.

Plate 42 x 6000 Detail of Plate 41 showing growth over aggregated particles.

Plate 43 x 3200 Moderately early stage of quartz crystal growth over aggregate suggesting a period in slow moving water of high silica concentration; unimpeded and unabraded crystal growth.

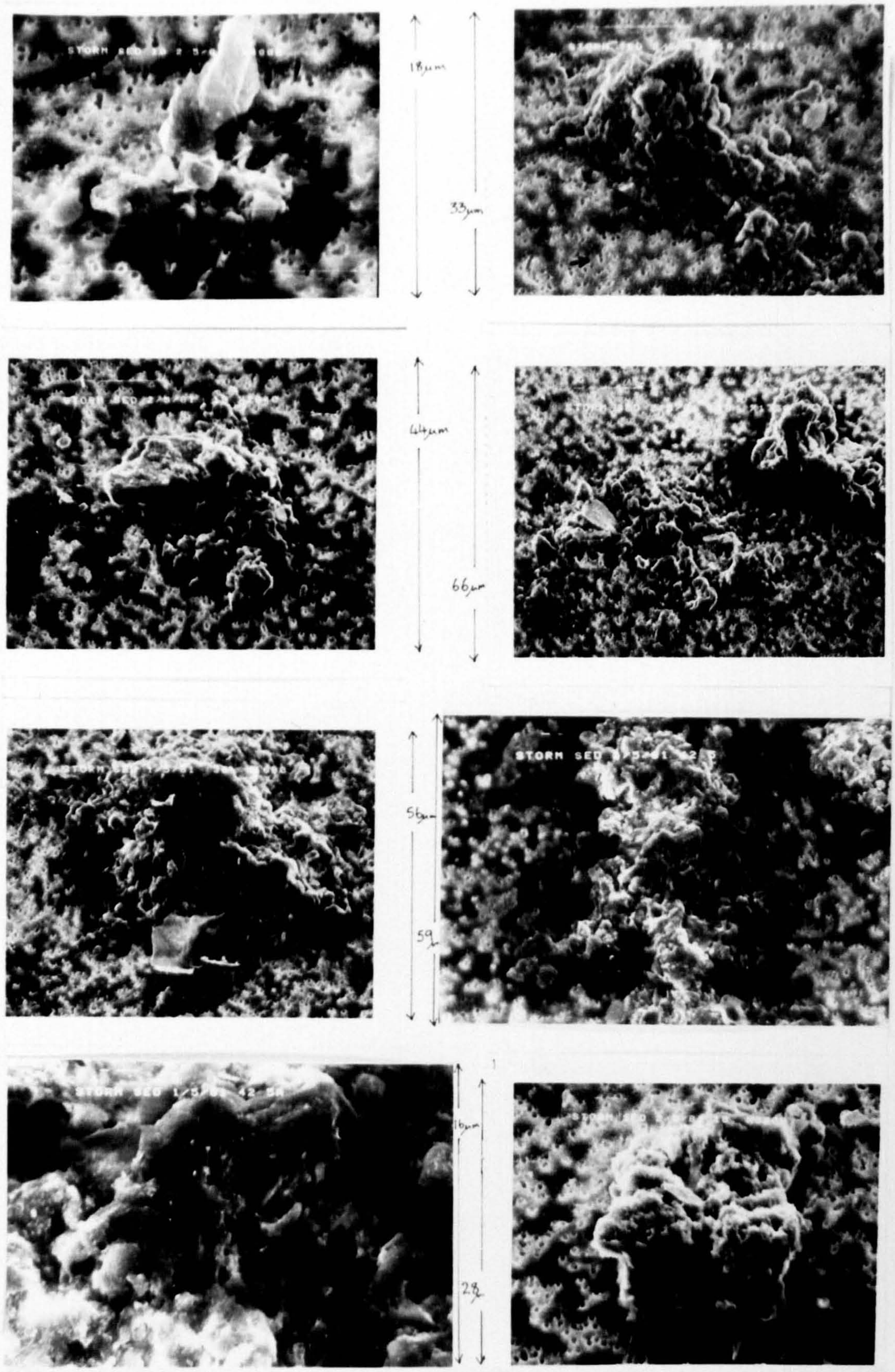

18μm
33μm
44μm
66μm
56μm
59μ
16μm
28μ

Plate 44 x 9800 Detail of Plate 43.

Plate 45 x 1500 Well-developed stormwater aggregate.

Plate 46 Energy dispersive x-ray analysis (EDXA) overall scan of aggregate (Plate 45) showing dominance of silica.

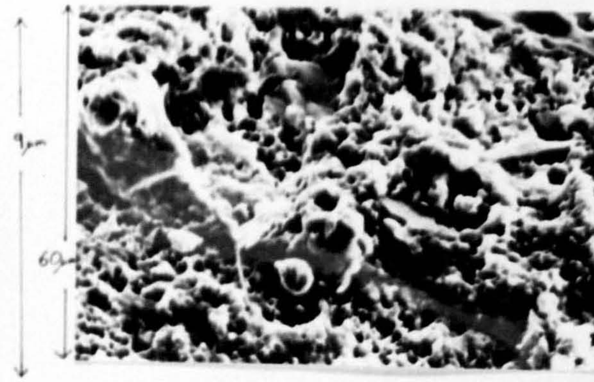
Plate 47 x 2700 Detail of Plate 45, development of silica precipitation on particle surface.

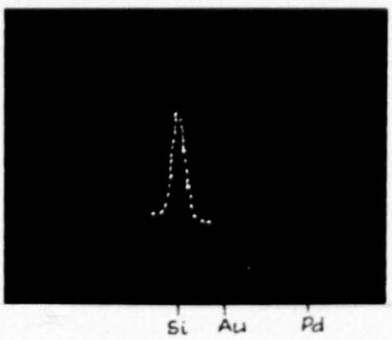
Plate 48 Elemental composition of precipitate shown in Plate 47.

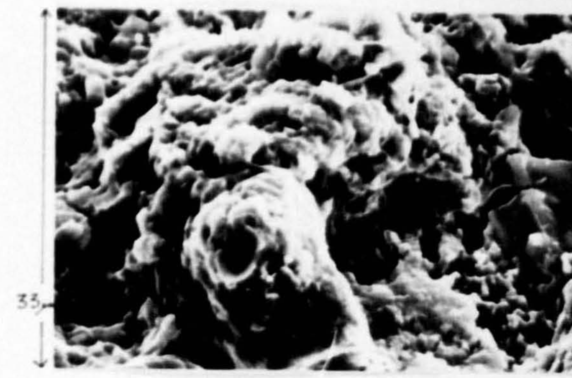
Plate 49 x 1000 Mid-storm aggregate.

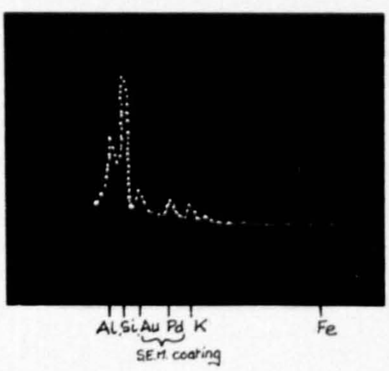
Plate 50 Elemental composition over aggregate (Plate 49) dominated by silica with aluminium, sulphur, potassium and iron (calcium = marker, not in sample).

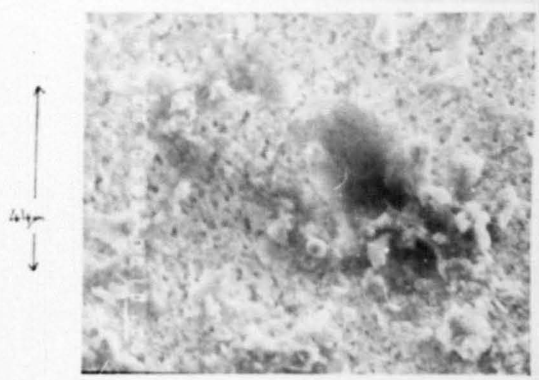
Plate 51 x 2600 Angular, fresh-faced road particle collected in stormwater sediment.

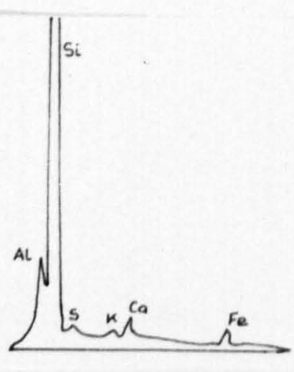

9μm
60μm


Si
Au
Pd


33μm


Al
Si
Au
Pd
K
Fe
SEM coating




Si
Al
S
K
Ca
Fe


13μm

Plate 52 Elemental spectrum of angular particle (Plate 51) showing dominant elements of silica and aluminium with substantial subsidiary peaks of calcium and iron.

Plate 53 x 1000 Overall view of weathered and eroded stormwater sediment from early in storm 16.11.81 (Sample 2) before aggregation increases.

Plate 54 x 3600 Detail of particle from Plate 53 with early stage of surface silica precipitation.

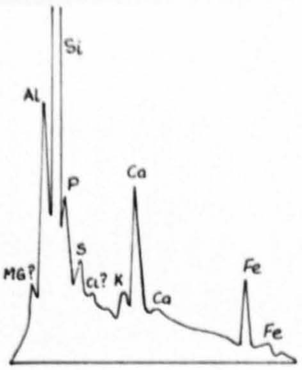
Plate 55 Elemental spectrum (Plate 54) dominated by silica with subsidiary peaks of calcium and iron.

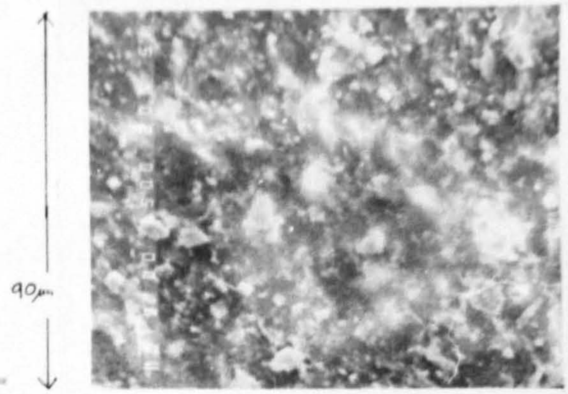
Plate 56 x 3600 Early stormwater sample of silica precipitation on adhering particles (nucleopore filter).

Plate 57 Spectrum of particle surface (Plate 56) strongly dominated by silica with subsidiary peaks of calcium and iron.

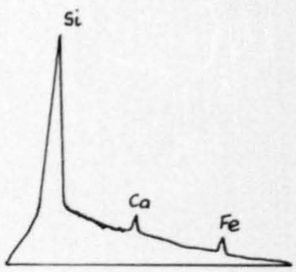
Plate 58 x 2400 Developing aggregate representative of mid-storm and individual particles.

Plate 59 Overall elemental composition of stormwater sediment (Plate 58) demonstrating the majority of elements commonly found in this study.

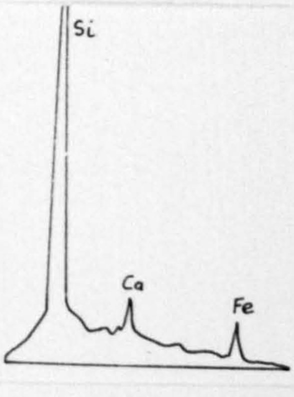

Si
Al
P
Ca
S
MG?
Cl?
K
Ca
Fe
Fe

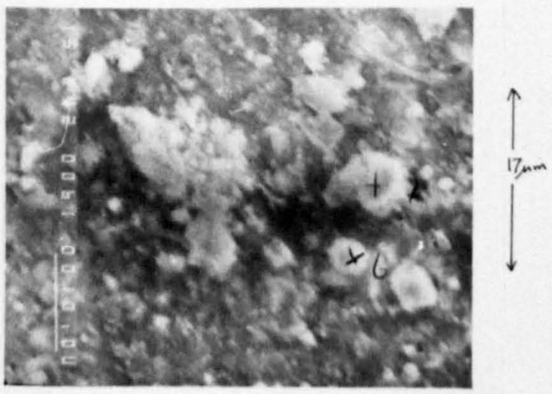

90µm


5µm


Si
Ca
Fe


7µm


Si
Ca
Fe


17µm

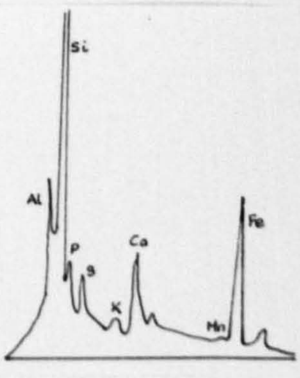

Si
Al
P
S
Ca
K
Mn
Fe

Plate 60 Elemental composition (spot analysis) of particle (Plate 58) showing a variety of elements present although dominated by silica and aluminium.

Plate 61 Spectrum of particle 7 (Plate 58) solid line, dominated by silica, alumium and potasium; broken line spectrum of particle '6' for comparison notably demonstrating the higher level of iron present in particle 7.

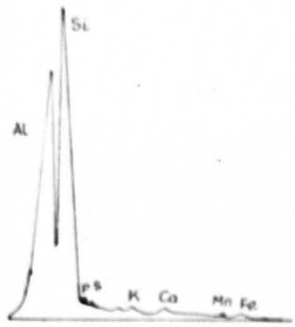
Plate 62 x 5400 Early storm stage of aggregation; elemental composition of abraded particle shown in Plate 63; nucleopore filter aperture (→).

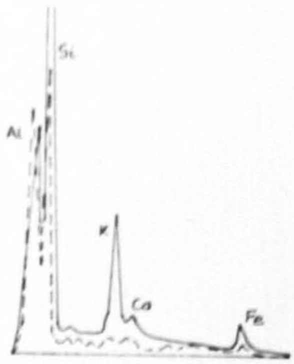
Plate 63 Particle (Plate 62) spectrum dominated by silica and aluminium, with potassium calcium and iron.

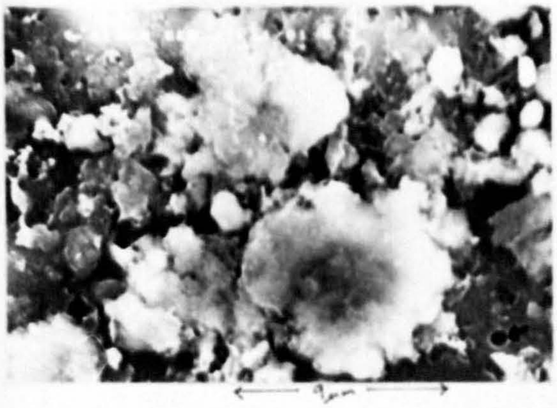
Plate 64 x 8500 Overall view of early storm aggregate.

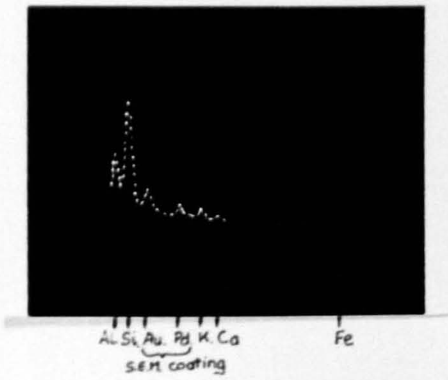
Plate 65 x 11400 Detail of aggregate (Plate 64).

Plate 66 Reduced-area scan of aggregate (Plate 65).


Si
Al
P S
K
Ca
Mn
Fe


Si
Al
K
Ca
Fe




Al Si Au Pd K Ca
Fe
S.E.M. coating

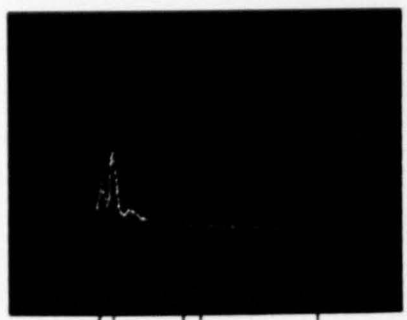

Al Si
K Ca
Fe

Plate 67 x 14000 Individual particles exhibiting surface silica precipitation of early storm.

Plate 68 EDXA Plate 67.

Plate 69 x 5900 Stormwater sediment mid-late storm, quartzitic particles, possibly with clays (see Plate 73).

Plate 70 Overall scan of elements in loose aggregate particles (Plate 69).

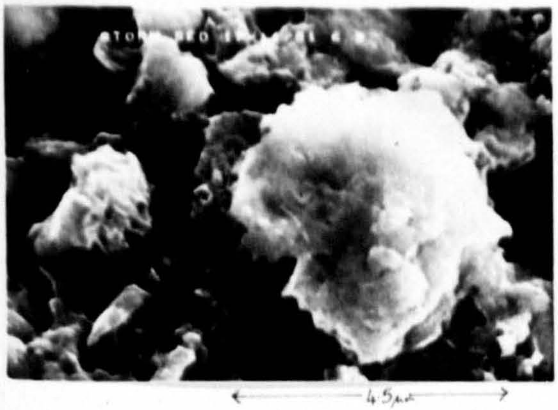
Minority Particle Types.

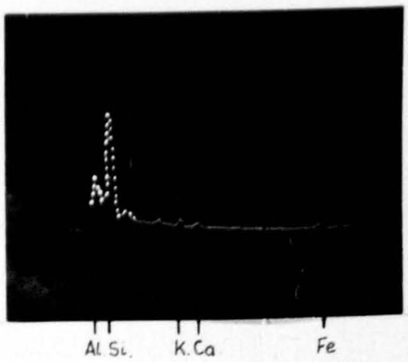
Plate 71 x 5400 Late-storm sediment, dominated by clays, possibly, of flaky appearance originating from bricks or roof tiles.

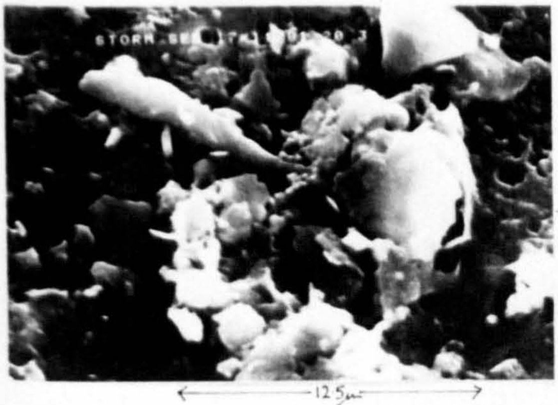
Plate 72 Elemental composition of sediment (Plate 71) dominated by silica.

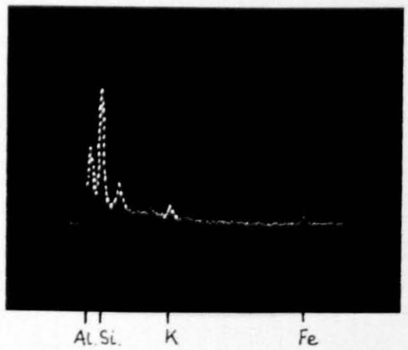
Plate 73 x 8900 Aggregation of quartzitic and clay particles.

Plate 74 Elemental composition of sediment (Plate 73).

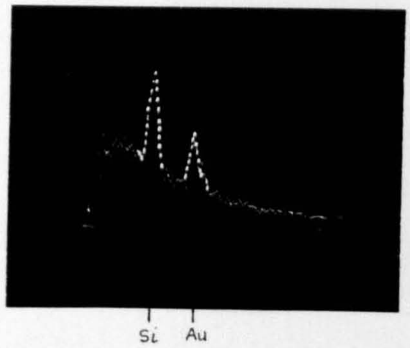

4.5μm


Al. Si.
K. Ca
Fe

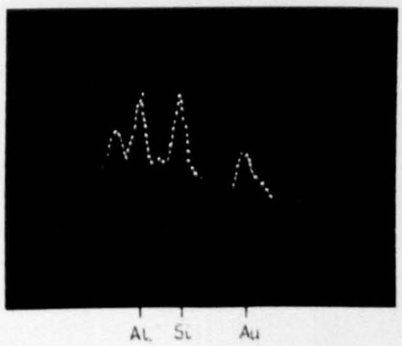

12.5μm


Al. Si.
K
Fe


16μm


Si
Au


10μm


Al.
Si
Au

Examples of Diatom Tests Found Early in Storms.

(See also Chapter 3)

Plate 75 x 6000 Separated test of dead diatom, length 9.5μm.

Plate 76 x 8600 Separated and cracked test of dead diatom, length 13μm.

Organic Material

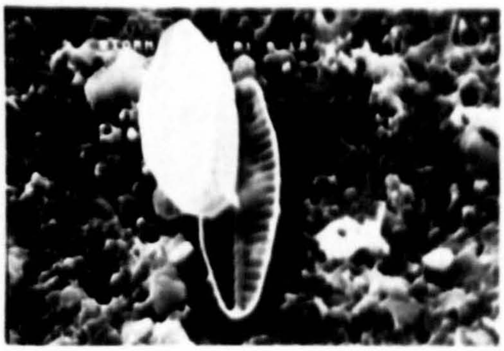
Plate 77 x 2700 Roughly spherical with convoluted surface, possibly of organic origin.

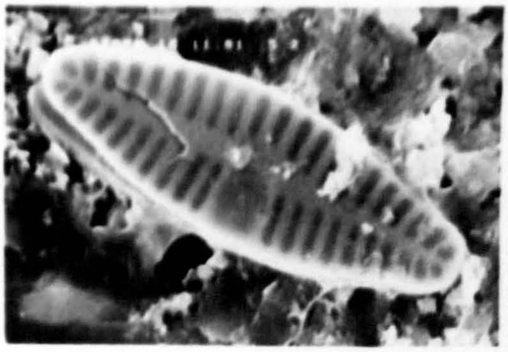
Plate 78 x 111700 Detail of Plate 72, with small angular fragment, probably of silica.

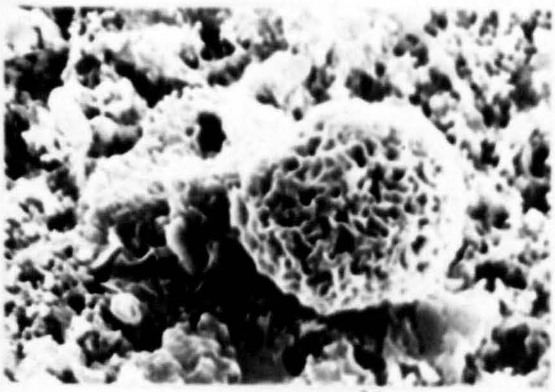
Plate 79 Reduced-area scan of Plate 78.

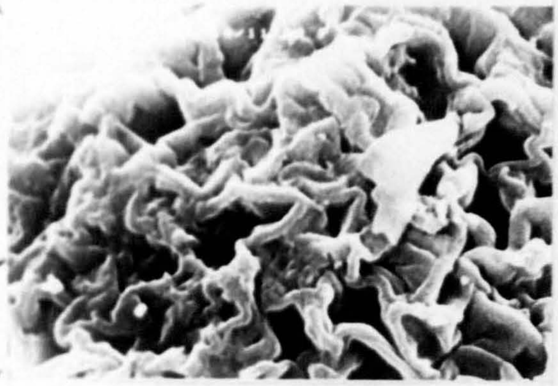
Plate 80 x 27000 Pollen grain.

Plate 81 Elemental composition of pollen grain.


13µm

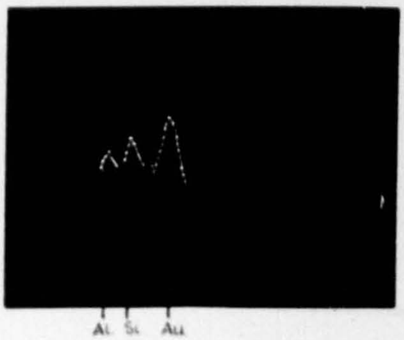

9µm


20µm


5µm


Mg? Si S Au K/Fe ?


0.5µm


Al Si Au

irregular hollows (Plates 82-99) or of relatively well developed crystals from evaporation after a prolonged period of slow drying out of the sewers. Crystal development like that shown in for example Plate 100 has been recognised in sedimentary environments and is attributed to the very slow precipitation of secondary silica in a high energy chemical environment (McKenzie and Gees, 1971). A number of authors including Waugh (1965, 1970), Pittman (1972), Austin (1974), Marzolf (1975), Simpson (1976), and Wilson (1978, 1980) have studied crystal growth on Millstone grit and sandstones and all agree these are three stages of development of overgrowths. Secondary silica has been found to precipitate after pressure solution during sedimentation (Wilson, 1978), but this is not applicable to the stormwater sediment, or during periods of supersaturation of silica-bearing ground waters (Austin, 1973). In the stormwater however the dominant process is most likely to be the precipitation of silica from high concentrations, encouraged by the sediment acting as the precipitation nuclei. The initial stage of crystal formation which is recognised in the literature is the development of small orientated prismatic or rhombohedral projections, which is dependent on the crystal orientation of the detrital host grain. With continued growth the projections merge and overlap to form well-defined crystal faces and eventually the grain is obscured by an almost perfect quartz crystal. Waugh (1965, 1970) found that Penrith Sandstone was cemented together by quartz

Plate 82 x 1000 Advanced aggregate development towards end of storm.

Plate 83 Spot analysis of central particle of aggregate (Plate 82).

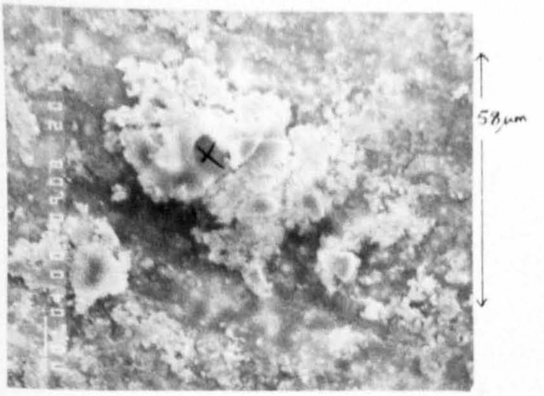
Plate 84 x 1400 Small aggragate mounted on carbon stub and carbon-coated.

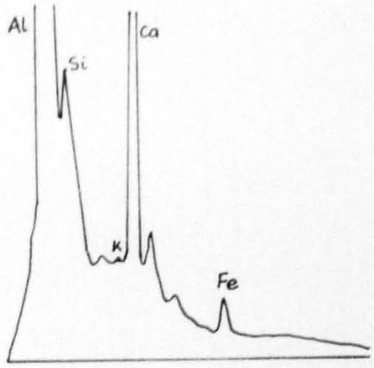
Plate 85 Spot analysis of particle 1 (Plate 84).

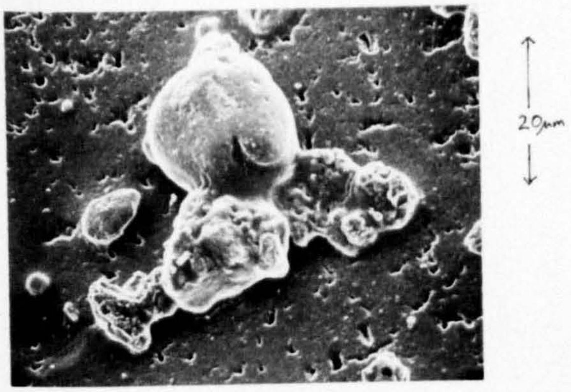
Plate 86 Spot analysis of particle 2 (Plate 84).

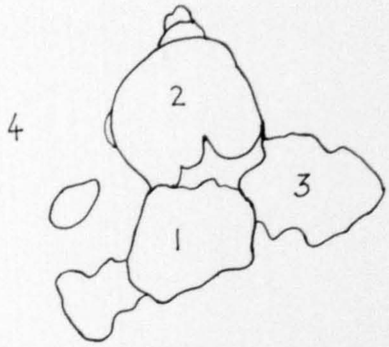
Plate 87 Spot analysis of particle 3 (Plate 84).

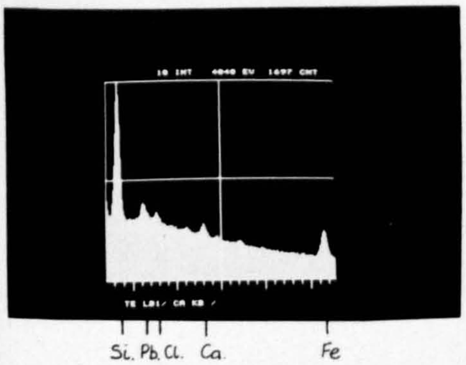
Plate 88 Background analysis of carbon stub (Plate 84) for comparison with sediment analysis.

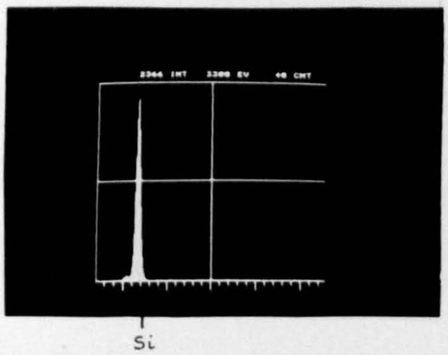

58μm

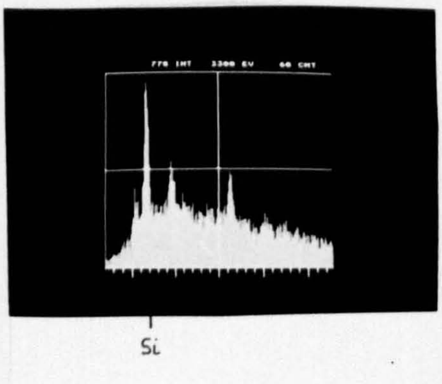

Al
Si
Ca
K
Fe

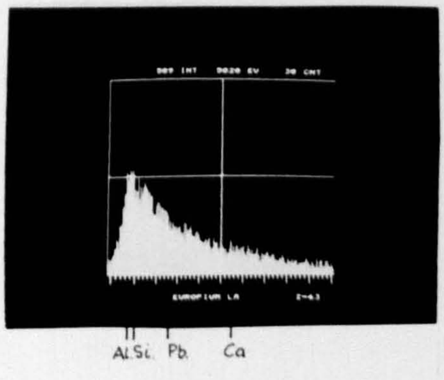

20μm


4
2
3
1


Si. Pb. Cl. Ca. Fe


Si


Si


Al Si. Pb. Ca

Well-Developed Silica Coating.

Plate 89 x 4100 Widespread silica precipitation; overall low relief.

Plate 90 x 1700 Well-developed silica precipitation and solution features on angular aggregate.

Advanced Silica Precipitation on a Small Aggregate.

Plate 91 a x 1150 b, c, d x 2600
Advanced silica precipitation on aggregate.

Plate 92
EDXA point 1.

Plate 93
EDXA point 2.

Plate 94
EDXA point 3.

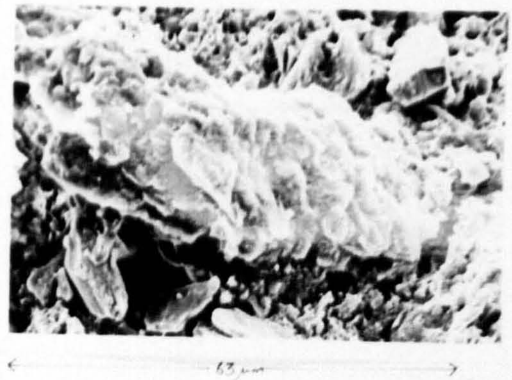
Plate 95
EDXA point 4.

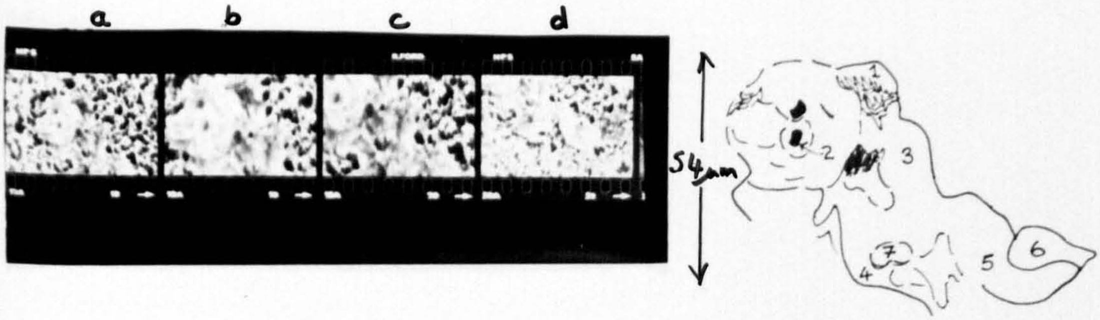
Plate 96
EDXA point 5.

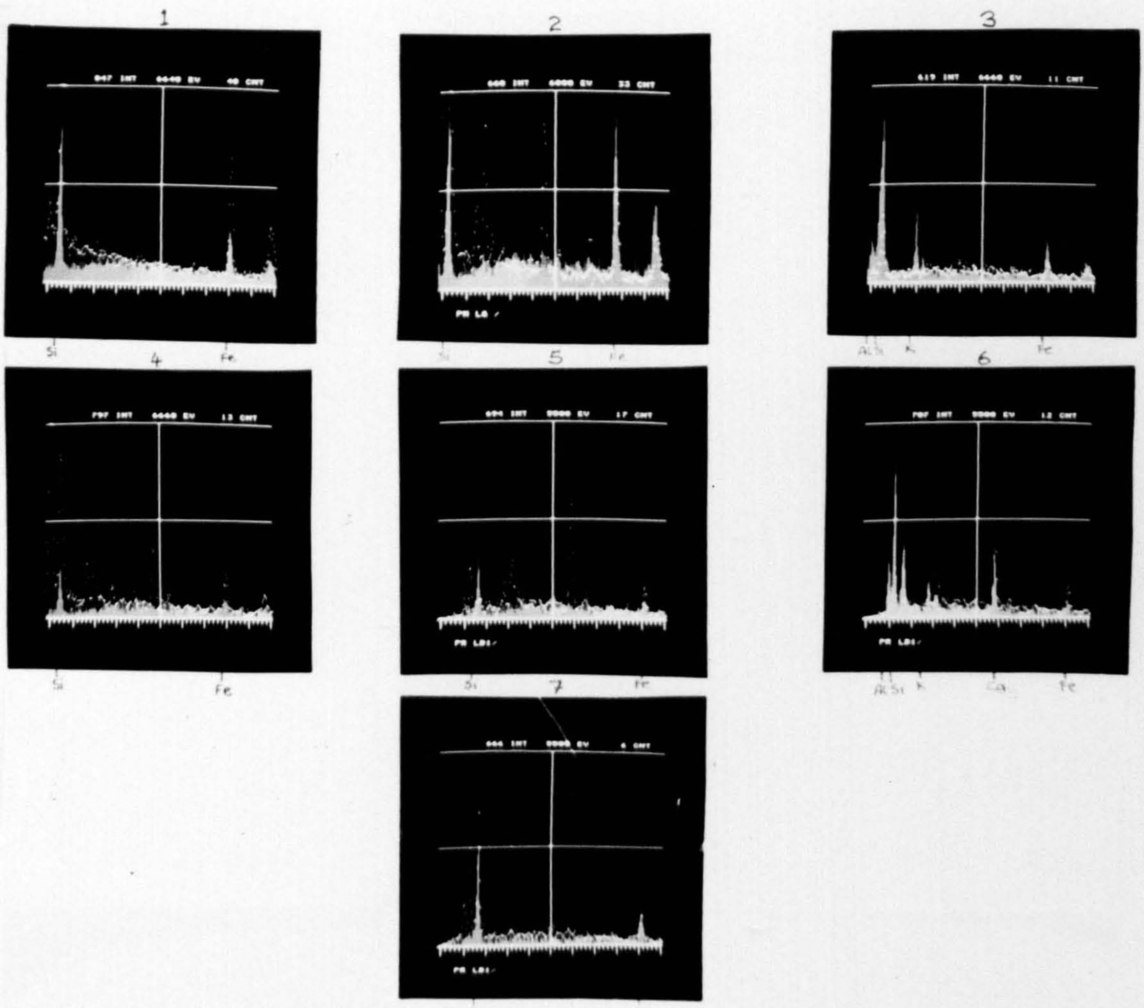
Plate 97
EDXA point 6.

Plate 98
EDXA point 7


25 µm


63 µm


a
b
c
d
54µm
1
2
3
4
5
6
7


1
2
3
Si
Fe
Al Si
K
Fe
4
5
6
Si
Fe
Si
Fe
Al Si
K
Ca
Fe
7

Silica Features on Individual Angular Particles.

Plate 99 x 4900 Small particles adhering and cemented to precipitated silica.

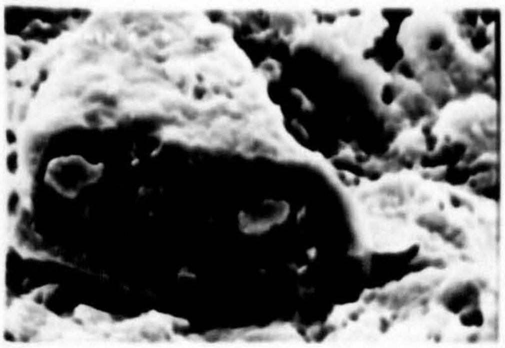
Crystal Growth.

Plate 100 x 5000 Extended growth of crystals, probably, quartz, from high silica concentration in evaporating drainflow; crystals are subjected to subsequent abrasion and solution.

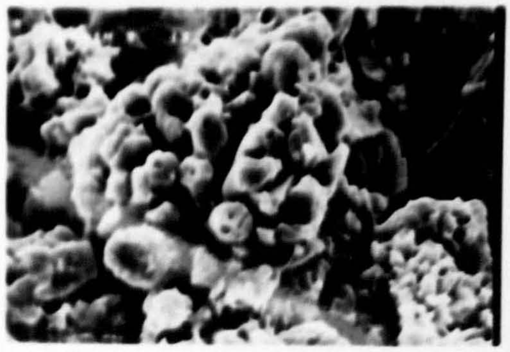
Silica Frosting.

Plate 101 x 1900 Frosted aggregate with clear-faced particles.

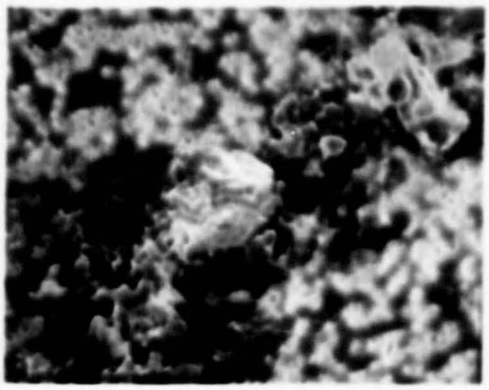
Plate 102 x 4800 Silica frosting on aggregated particle; nucleopore filter background with silica frosting.



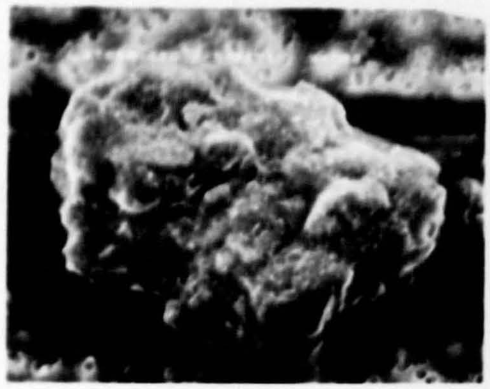
18 μm



15.5 μm



17 μm



20 μm

overgrowths which appear to be very similar to the aggregated form of the stormwater sediments. This suggests that the stormwater aggregates were formed in this way.

Silica frosting (Plates 101, 102) is the low density of particles with secondary silica of granular appearance (Lucchi, 1970; Margolis and Krinsley 1971). This form of silica precipitation is the result of increasing silica concentration and as such may be considered as the very early stage of overgrowth formation on the stormwater sediment. The feature is classed as diagnostic of stormwater sediment and covers either part (Plate 101) or all of the aggregate (Plate 102). It must be recognised however that where the entire aggregate is covered by frosting which does occur in a minority of samples, the surrounding individual grains and blank filter are also affected. This suggests that in these instances the feature may be created or accentuated by the filtration process during which the concentration is rapidly increased causing precipitation both then and during the subsequent evaporation in the drying of the filter.

Although the majority of the sediment develops silica precipitation features a few particles remain unaffected. This may be due to the recent input of the sediment in instances when it is transported rapidly through the drain with renewed rainfall and discharge. Such sediment does however suffer considerable abrasion by the drain transport process and thus becomes noticeably rounded and eroded compared with the sediment which remained

Angular Abraded Individual Particles.

Plate 103 x 9000 Conchoidal and straight steps on angular particle.

Plate 104 x 16000 Fresh-faced angular particle with conchoidal breakage.

Plate 105 x 8800 Angular particle of jagged outline and adhering fine particles which appear to be fragments off the main particle; an abundance of step features is possibly the result of cleavage breaks. (Relief reduced to sharpen edge detail).

Plate 106 x 9000 Angular, fresh-faced particle with silica development on one edge.

Plate 107 x 8100 Fine, flaky fragments, possibly clays, adhering to parent or other particle.

Subrounded Individual Stormwater Particles.

Plate 108 x 8100 Particle free from silica features; spherical aperture of nucleopore filter.

Plate 109 x 8700 Minimal silica development and "webs" of silica or clays.

Plate 110 x 9100 Fresh-faced particles and quartz crystalline development.

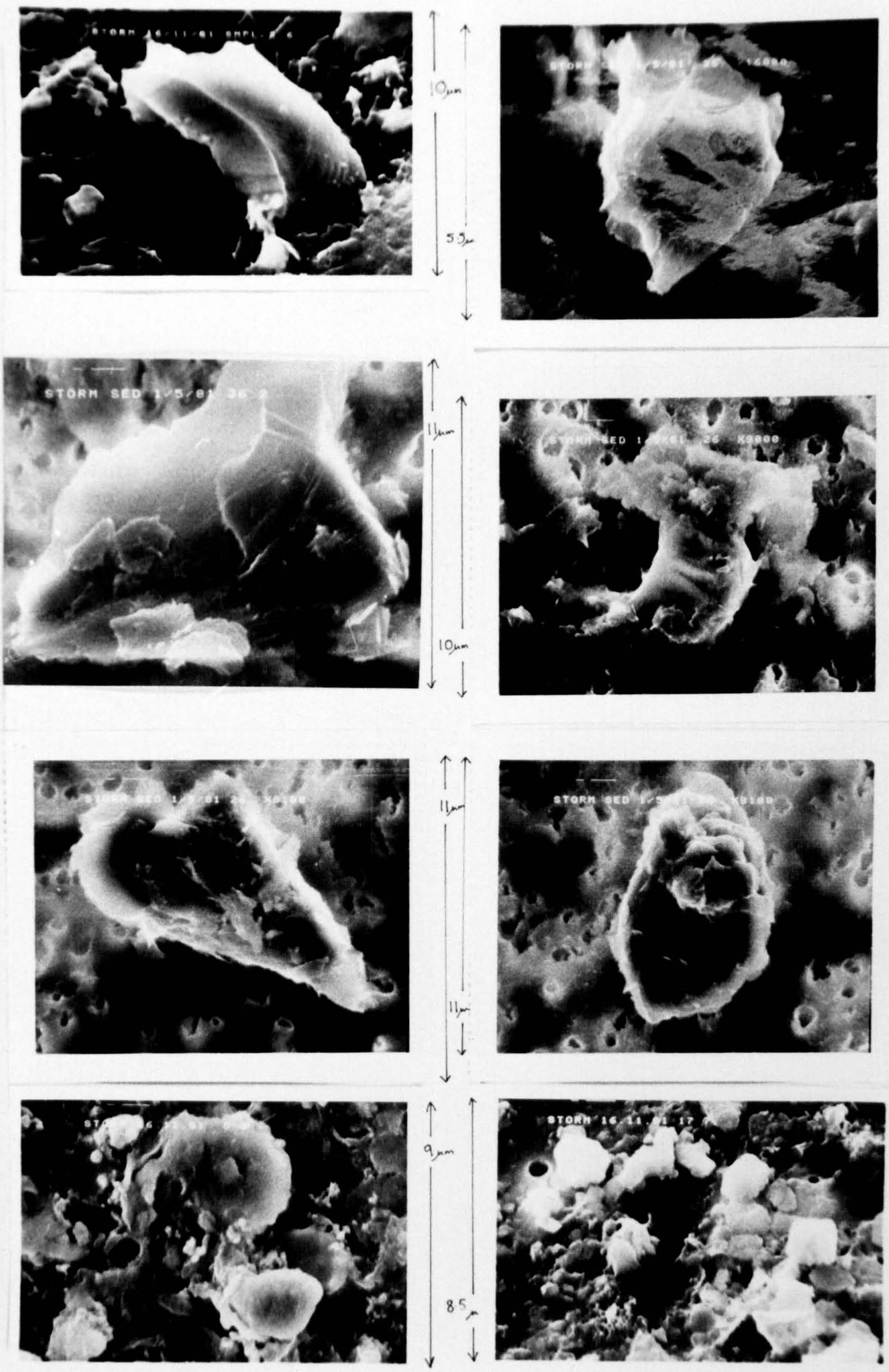
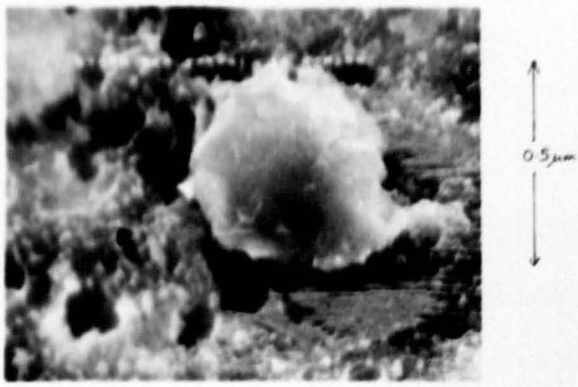

10μm
5.5μm
11μm
10μm
11μm
11μm
9μm
8.5μm

Plate 111 x 20200 Abraded, subangular, idividual particle.


0.5µm

on the land surface (Plates 103-111.)

Striations, 'V' notches and ridges are features described widely in the literature as being the result of abrasion in natural river transport. Such features are rarely recognised on the stormwater sediment and it is suggested that the omission may be due to the smaller size of this sediment compared with that of river-borne material. The lack of such features and the relatively low degree of rounding can be explained by the relatively short distances and times of travel in this urban sewer system. Conversely, the system has higher ionic concentrations than a natural watercourse. (Gavens et al,1981). From the artificially rapid input of water and sediment from the impermeable urban surface into the constricted flows, combined with frequent surcharging conditions in sewer transport (Colyer and Pethick, 1977), sediment may suffer greater discemination.

7.5. Surface Textures Created By Land Use.

The aim of this study was to determine more detailed sediment sources within the catchment.

Seven different types of land use were recognised in the catchment and are delineated in Figure 2.1. The areas of modern housing were divided into three classes based on building material and hence sediment composition. A fourth class of housing comprised much older Victorian and inter-war property which generated very well weathered sediment. The shopping area warranted a separate class for the variety of sediment generated, as did the main road across the southern section of catchment which carries a considerable volume of heavy commercial traffic and is lined by depots and warehouses (Chapter 2). Finally, the class covering the largest area of the catchment is "open spaces" from which soil particles in stormwater runoff were sampled. Mention is also made here of the railway although its sediment is not distinctly recognisable at the outfall.

The land use determines the diagnostic features of the sediment generated as can be seen in Table 7.4. The sediment in modern housing Areas 2 and 5 is characteristically fresh-faced and angular; silica precipitates and aggregates predominate in the older developed Areas 6, 8, and also in the unusually high concrete

Area 1; brick clay fragments predominate in Area 3 and soil aggregates in Area 4. However sediment is altered on the surface by weathering and erosion and may be transported between adjacent areas before being washed into the drainage system. As a result, many features of the sediment transgress these general divisions.

All the features of abrasion are well-developed and relatively extensive but with silica precipitation and solution features

TABLE 7.4. FUZZY ANALYSIS OF LAND USE SEDIMENT SAMPLES.

Sample / Feature	1 Housing Concrete		2 Modern Housing		3 Bricks Shops		4 Soil		5 Modern Housing No Gardens		6 Old Housing		7 Aerodrome Road	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A Aggregate @	1.5	52	3.3	33	2.1	41	3.2	59	2.8	50	2.0	25	3.0	39
B Si. Features	3.4	59	3.9	58	3.5	59	2.3	91**	2.9	88**	3.5	100**	3.4	69
C Pitting	2.5	34	3.0	33	2.8	35	1.6	36	2.8	31	3.0	25	2.5	77*
D Fresh Face	3.3	59	3.3	75*	3.0	71*	3.1	86**	4.1	50	2.4	63	2.8	92**
E Angularity	3.4	52	3.5	92**	2.9	82**	2.9	86**	3.8	63	2.8	63	3.2	85**
F Steps	1.6	52	1.3	50	1.5	35	1.9	77*	2.1	63	2.0	38	1.8	46
G Impact Pits	3.0	63	3.2	92**	2.6	82**	3.2	82**	2.6	88**	3.3	75*	2.6	100**
H "Crinkles"														
I Clays	5.0	11					6.0	5	5.0	6				
J Sphericals	5.0	7			5.0	12			5.0	6	5.0	13		
K Flyash														

@ Feature list given in Table 7.3.

μ = Mean fuzzy value of feature from sample particles.

% = Percentage of particles with feature.

71* = Notable values, 70–79

100** = High values, 80–100

providing clear evidence of a period in water. The precipitation and solution features were expected as a result of the samples being taken from stormwater runoff in gutters. Angularity, fresh featureless surfaces, and impact marks vary together. High values for each one demonstrate the predominant presence of durable sediment in areas of modern housing (Plates 112-116). Similar hard particles have been found from weathered brick material in Area 6 and in freshly weathered material from most areas, particularly Areas 6 and 7. It seems likely that quartz from roadstone and building materials makes up most of this material since such sediment is absent from the samples taken from areas of modern housing where the sediment is affected by the presence of concrete in driveways.

By comparison, the greater degree of weathering and erosion in sediment from older housing areas, and from areas of high erosion rates caused by traffic, can be seen in Plates 117-122. Silica precipitation and solution features produced by weathering products are at a maximum in these areas and lead to inter-particle cementation and aggregate formation. Similar features are shown in samples from the modern housing area with concrete drives where silica is relatively easily released by weathering. Pitting too is best developed and most extensive in these areas but it occurs more frequently in drain sediments and may be assumed to be the result of prolonged erosion. It is important to note that silica precipitation, solution features and the early stages of aggregation occur in recently built areas although they are more poorly developed and markedly less frequent than those in the sewer

SEDIMENT FROM DIFFERENT LAND USES

Modern Housing: Fresh Sediment and Early Alteration.

Plate 112 x 4100 Overall view of individual, angular, fresh-faced sediment.

Plate 113 x 1000 Angular particle with adhering fragments, some cemented by early aggregation possibly on 'sheltered' downstream side of particle during stationary period in runoff.

Plate 114 x 1500 Angular, fresh-faced particle with aggregate developing from silica cementation of adhering particles.

Plate 115 x 1000 Large, angular, fresh-faced particle with adhering fragments and surface precipitation, surrounded by fine angular, fresh-faced particles and isolated precipitation; small aggregate, possibly brick material (→).

Silica Precipitation and Solution Features.

Plate 116 x 2600 Precipitation and solution (centre) but predominantly angular fresh-faced fine particles.

Plate 117 x 2600 Silica precipitation (a), (b), (c), fresh-faced, angular fragment incorporated into aggregate (d); also subrounded particle with precipitation-solution surfaces, incorporated.

Plate 118 x 2600 Small aggregate formed from well-weathered particles; clay particle, possibly montmorillonite, from soil (a), precipitation (b).

Plate 119 x 2300 Large fresh-faced particle with surface precipitation (a) and impact features (b).

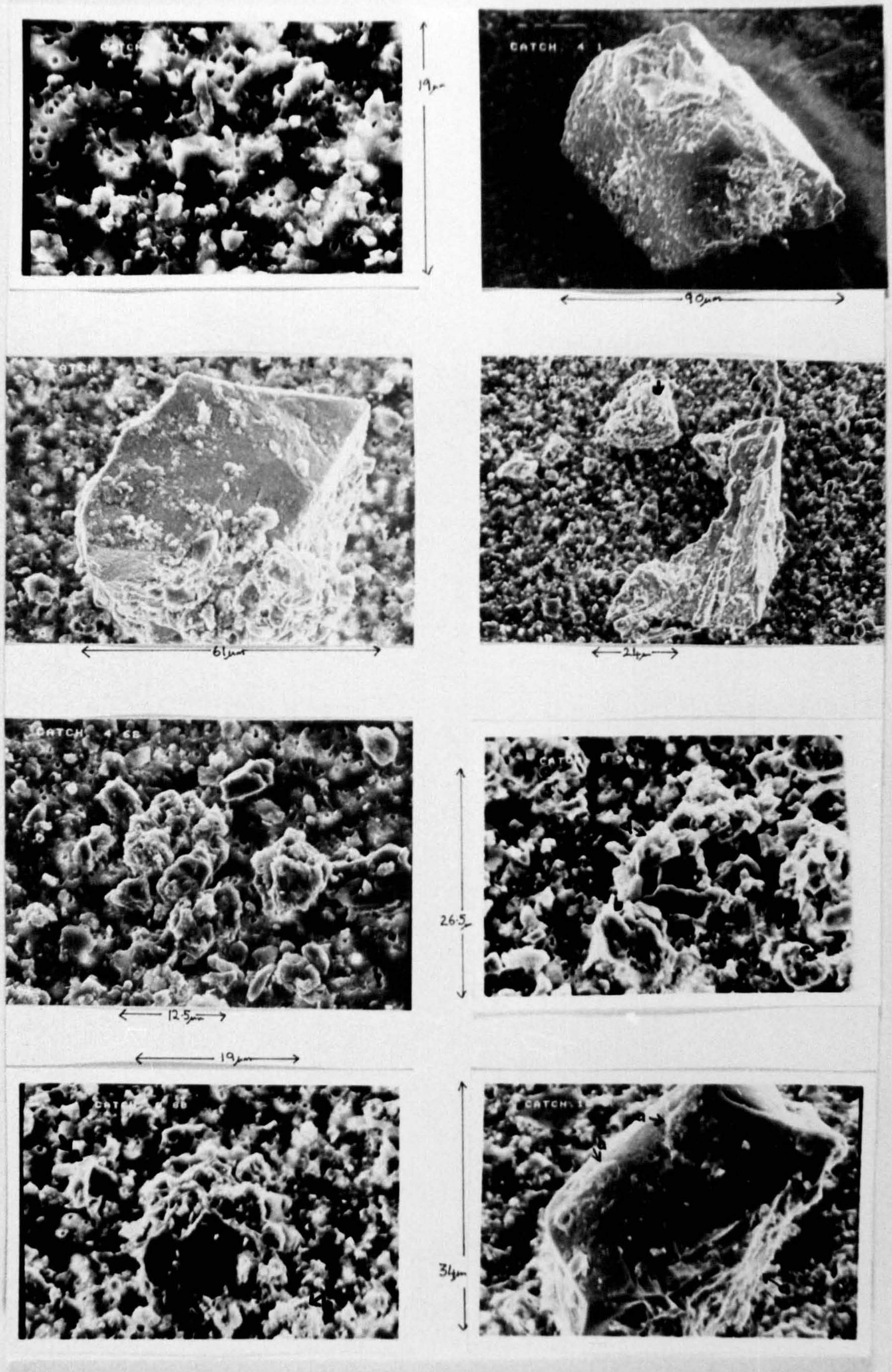

19μm
CATCH. 4 1
90μm
61μm
21μm
CATCH. 4 6B
12.5μm
26.5μm
19μm
34μm

Plate 120 x 7200 Weathered particle with well-doveloped silica precipitation and solution feature attached to aggregate.

Plate 121 x 12700 Stalked, living diatom providing evidence of abundant free silica.

Sediment of Brick Building Material.

Plate 122 x 840 Overall view of aggregate, possibly from bricks showing fresh and weathered fine particles, diatoms and occasionally, spherical particles.

Plate 123 x 630 Typical brick sediment, aggregated sediment from entirely brick-built shopping area; irregular particle surface and cement; rounded surface indicates weathering.

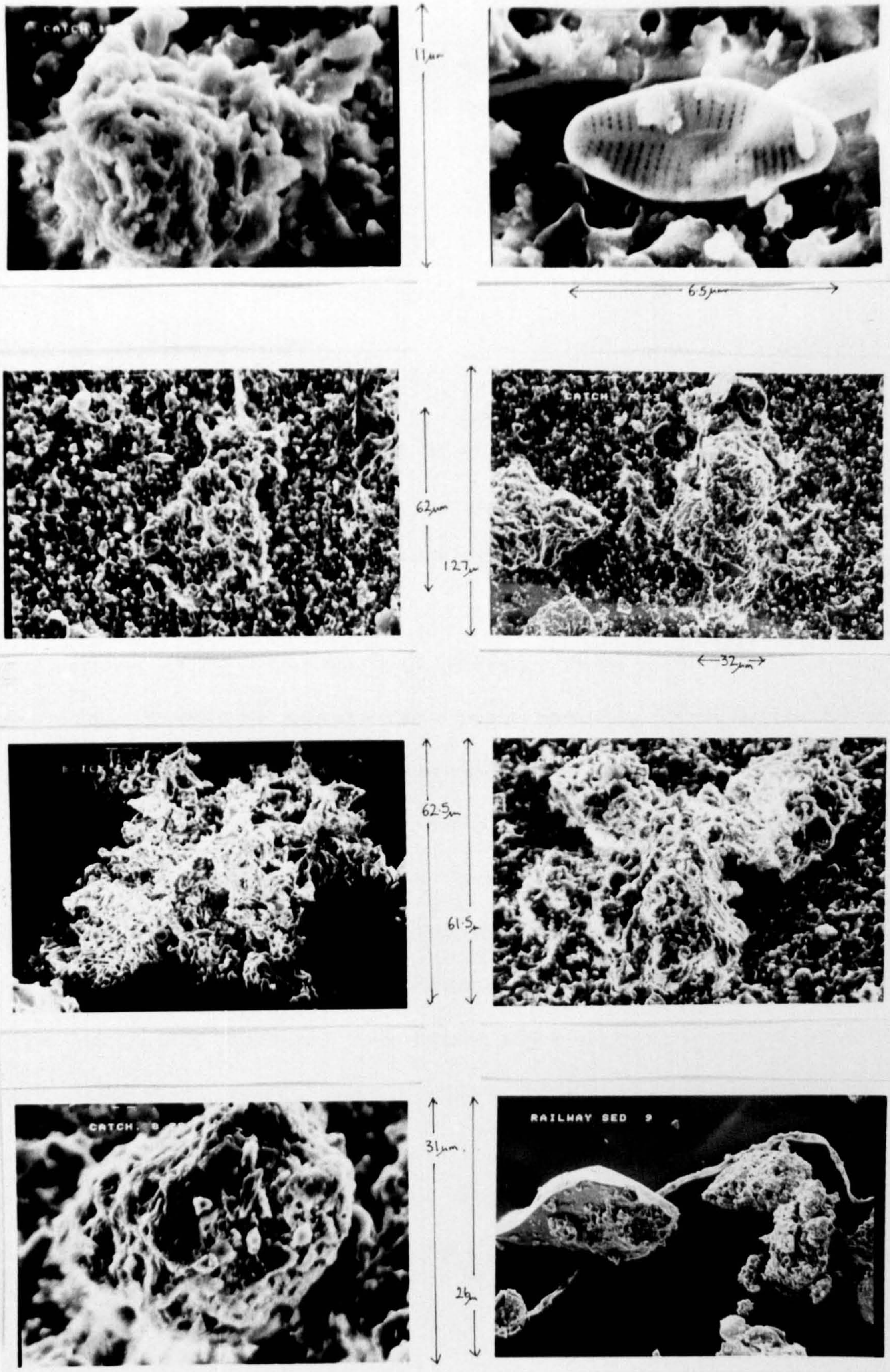
Plate 124 x 1280 Control brick clay for comparison; similar make up of land use sample but more angular due to lack of weathering.

Plate 125 x 1300 Brick aggregate from old housing area showing considerably more advanced weathering, surface rounding and solution and precipitation.

Railway Sediment.

Plate 126 x 2600 Detail of weathered brick aggregate with surface precipitation.

Plate 127 x 3000 Abraded, angular, fresh-faced particle (left) with adhering fines and early cementation and aggregation; small aggregates with precipitation and solution surfaces.



11μm
6.5μm
62μm
CATCH
127μm
32μm
62.5μm
61.5μm
CATCH
31μm
RAILWAY SED 9
26μm

system (Plate 113). This indicates that these processes of alteration (described an Chapter 3) occur in water and begin during sediment transport in surface runoff before entering the drain.

Living diatoms have been found in surface water such as the example in Plate 121 which conforms the presence of silica (Chapter 3) in the runoff.

The weathered brick sediment is distinctive and forms a large proportion of the sediment sampled in Area 4. Plates 123-126 show this distinctive material which appears to be aggregates comprising of fine, mostly angular particles. Most samples have the appearance of weathering and display some precipitation development. They are noticeably more rounded than the freshly-eroded control brick fragment examined and shown in Appèndix 6 but they are nevertheless recognisable as brick fragments. These particles are not found, in this form at least, at the outfall. Either their clay constituents are unable to withstand the weathering and erosion during transport to the outfall, or they form the basis for further aggregate development with additional sediment from road runoff and further silica precipitation.

The mainline railway from Euston Station, London, is a feature of the catchment and has sediment which includes both individual and aggregated particles (Plates 127-131). The individual particles are angular with plain surfaces and adhering particles and early surface precipitation (Plate 129). More widespread precipitation can be seen but appears to have undergone considerable solution (Plates 130,131) Aggregates of the type in Plate 127 were sampled less frequently, comprise only a small number of particles but exhibit the same precipitation-solution features described above. Like the brick samples, the railway sediment in the form described is not easily recognisable in outfall samples.

Aggregation and silica precipitation and solution features are best developed in soil samples (Plates 132-135) taken both from open spaces and from areas of older housing with large gardens. The high silica content of circulating pore water in soils precipitates out of solution and aids aggregation even before transport in runoff. As can be seen from the soil photomicrographs these aggregates and silica surfaces are more rounded and of lower relief than in stormwater where strongly erosive transport prevails. In addition, areas of older housing have the greater decay of building materials to release elements of which silica occurs most frequently (Shirley, 1981) (Plates 120, 125)

Very little was seen of clay minerals in the runoff samples although they would be expected to be present from brick decay. It seems likely therefore that they are finely broken down by weathering and are too fragile to withstand sewer transport and as such are no longer clearly recognisable on micrographs.

Plate 128 x 3000 Abraded angular fragment with adhering fines (top); aggregate developing on angular particle (middle); surface precipitation (low).

Plate 129 x 3000 Detail of Plate 128, early stages of precipitation over particle surface.

Plate 130 x 3000 Precipitation and aggregation on particle surface, in early stages.

Plate 131 x 6000 Detail of Plate 130, solution and pitting features in the precipitate.

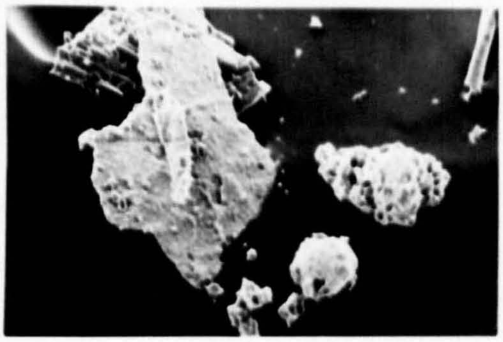
Soil Aggregates and Clay Particles.

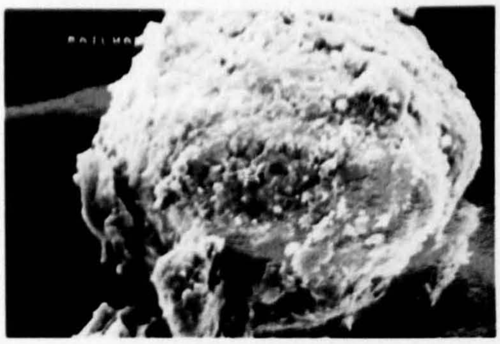
Plate 132 x 4900 Substantial soil aggregate with both angular, fresh-faces and early precipitation; surrounding angular and rounded, fine individual particles.

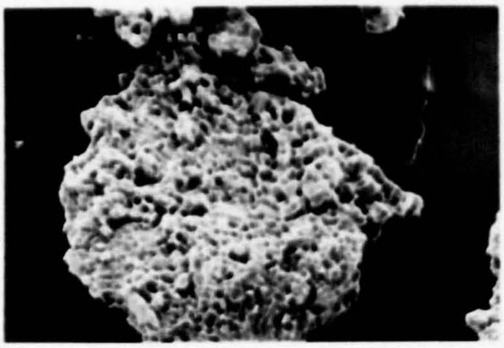
Plate 133 x 1530 Angular soil particle with precipitation and aggregation; precipitation features also common on surrounding individual material.

Plate 134 x 1530 Aggregation on angular, weathered, individual, large particle.

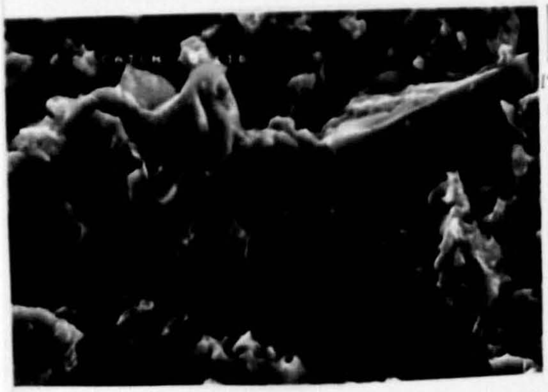
Plate 135 x 3200 Clay particles recognised as montmorillonite.


26µm

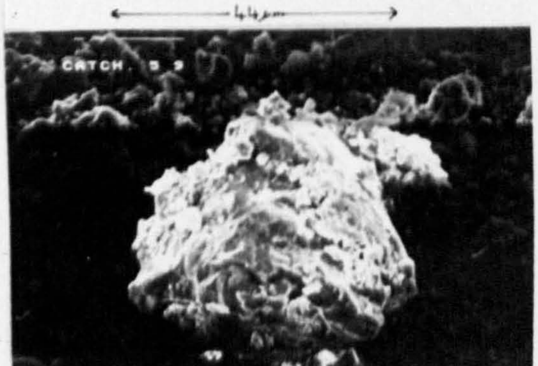

26µm


26µm


12µm


18µm


40µm


44µm
CATCH. 5.3


7.5µm

Plate 135 shows the only recognisable clay particle, which can be indentified as montmorillonite, (McCrone 1973-80).

Only a small number of airborne particles were sampled at the outfall (Plates 136, 137) but it can be seen that some of the particles washed on to the surface had been affected by abrasion (Plate 137) and precipitation (Plate 136).

In conclusion, it can be seen that the method is sufficiently stringent to discriminate between fresh angular material from modern areas and the far greater abrasion of the sediment from the older areas. The greater availability of silica for aggregation and features of precipitation and solution can be seen in areas of open space and in samples that have undergone advanced erosion. The method has also proved sensitive enough to indicate the presence of the high levels of silica in the friable concrete, from driveways, (Sample 1, 117, 118) which too produces higher levels of silica than other areas of modern housing. Modern housing Area 5 stands out as an exception in that its abrasion features do not wholly conform to the pattern of the others. The features have an unusually high level of silica-cemented aggregates (Plates 114 and 115) comparable with the soil and older housing levels (Table 7.4.), which must be due to the building material being more friable and releasing more silica than in other similar areas.

Airborne Spherical Sediment.

Plate 136 x 4400 Spherical particle amongst weathered angular material; surface precipitation beginning in gutter flow; surface pitting. (old housing area).

Plate 137 x 14300 Spherical collected in modern housing area 1, amongst angular particles; abrasion features and adhering fragments.

DRAIN SEDIMENT.

Silica Activity in the Upper Catchment.

Plate 138 x 2340 Silica solution and precipitation on fresh angular sediment, silica from friable concrete drive sediment.

Plate 139 x 1390 Aggregation by plentiful silica, of freshly eroded sediment.

Angular Sediment.

Plate 140 x 1560 Angular Particles amongst silica precipitation and aggregation.

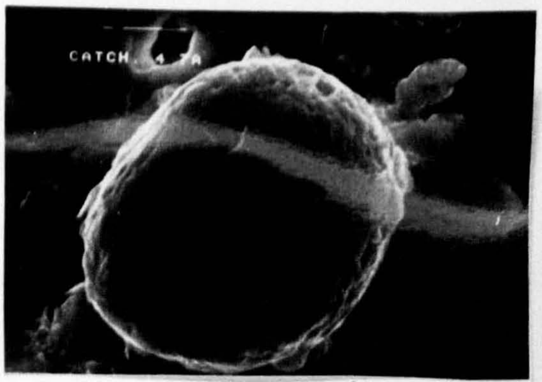
Plate 141 x 2340 Fresh-faced angular sediment from the head of the catchment and thus only slightly abraded.

Open Space Soil Particles.

Plate 142 x 5200 Angular fresh-faced particles with initial silica precipitation; aggregate in silica-rich concrete area.

Plate 143 x 7500 Rounded, silica-altered soil particles and pollen grains (→).

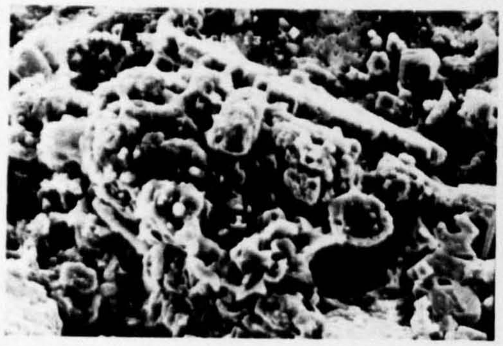
⟵ 5·5µm ⟶



⟵ 4·5µm ⟶

34µm

57µm

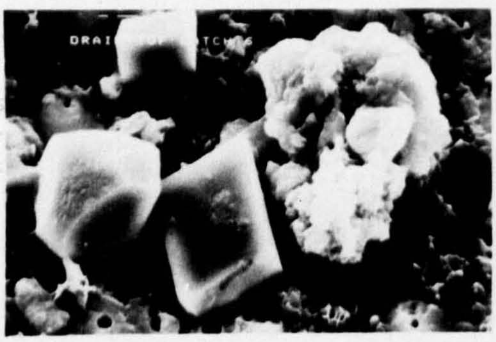


51µm

11·5µm

⟵ 6µm ⟶

⟵ 2·5µm



11·0µm

7.6. Texture Variations Along the Drain System.

Sediment samples were taken at points along the length of the storm drain, from the head of the catchment to the outfall, in an attempt to determine the effect of increasing time and distance of transport on the sediment. Sediment enters the main storm sewer along its length from the branched system of smaller side drains. Attempts were made to take into account the varying nature of sediment inputs from land uses adjacent to the sampling points along the drain system. It proved extremely difficult however, to discriminate between fresh sediment inputs coming from up-stream, and thus far little altered, and those progressively input from different areas along the drain.

Sediment from six sample points along the drain was examined using the Fuzzy Analysis technique. The results are summarised in Table 7.5 The sample point at the head of the catchment acted as a control with relatively fresh sediment entering the drain from a limited and well-defined sub-area of new housing. The second sample point roughly half way to the settling pond (Figure 2.1.) was in an area of modern housing and open space. Samples three and four were taken immediately above and below the settling pond respectively, to monitor the filtering effect of the pond within the drainage system. The fifth sample was taken immediately after the junction of the stormwater sewer with a neighbouring

TABLE 7.5.

FUZZY ANALYSIS OF DRAIN SEDIMENT SAMPLES.

Sample Feature	1 Catchment Head		2 Path		3 Above Pond		4 Below Pond		5 Junction	
	μ	%	μ	%	μ	%	μ	%	μ	%
A Aggregates @	4.5	72*	4.3	43	3.3	50	2.8	35	2.3	55
B Si. Features	3.5	100**	4.2	100**	3.9	91**	3.5	100**	3.6	82**
C Pitting	2.5	72*	2.0	35	2.4	59	2.7	41	2.2	46
D Fresh Face	2.2	72*	1.7	48	1.8	47	2.9	76*	3.3	64
E Angularity	4.2	83**	2.7	57	2.8	72*	3.9	71*	3.0	64
F Steps			1.3	35	1.7	19	1.9	53	1.8	46
G Impact Pits	1.4	88**	2.3	81	3.2	100**	2.9	82**	2.9	73*
H "Crinkles										
I Clays					3.0	3			4.0	9
J Spericals					5.0	3				
K Flyash										

@ Feature list given in Table 7.3.

μ = Mean Fuzzy value of feature from sample particles
% = Percentage of particles with feature
71* = Notable values 70-79
100** = High values 80-100

main branch sewer, approximately 350m upstream of the outfall (Figure 2.1.).

The results demonstrate a considerably different pattern across the catchment from those of the land use samples. The proportion of impact features remains moderate throughout although these results maybe slightly masked by the well-developed silica precipitation and solution features. The silica features cover the entire particle surfaces in three samples and are considered to be the result of drainflow. Although angular sediment with impact features does occur, the particles are substantially more rounded than the surface sediment. That too can be attributed to the abrasion and silica activity occurring during drainflow.

The results are slightly distorted because the first sample from the head of the catchment was taken within a housing area characterised by concrete driveways. The concrete is friable and provides a ready source of free silica. As a result there is a much higher degree of sediment aggregation and of features of silica precipitation and solution (Plates 138-140). Lower downstream the silica concentration diminishes owing to dilution but towards the outfall the concentration increases again as a result of the distance travelled by the sediment and of the time spent in the system. The degree of angularity of the durable sediment is at a maximum at the head of the catchment as would be expected in freshly weathered material with the minimum distance of abrasive transportation as can be seen from Plates 138, 141, and 142.

Sample particles taken from the drain in an open space area exhibit features of silica precipitation and solution (Plates 143, 146). Although the features have developed in the soil they are similar to those discussed in Section 7.5. above.

The settling pond has a marked effect. From a comparison of the results obtained the samples taken immediately above and below the pond the aggregates appear to have settled out while finer individual particles continue through the system (Plates 147-153). The individual particles are far more rounded than the fresh sediment coming in from the surface. These particles also display moderately high levels of well-developed silica precipitation and solution features resulting from their prolonged period and distances of travel in the stormflow. These results will be referred to again in Chapter 10, in conjunction with particle size data verifying the reduction of coarse material immediately downstream of the settling ponds.

The renewed occurrence of well-developed aggregates at the sample sites below the junction of the two main sewers is due to the other sewer having no settling pond. The results are shown in Plates 154-156.

Plate 144 x 7600 Angular, soil particles amongst well-weathered particles, quite distinct from other sediment samples.

Plate 145 x 7500 Soil particle aggregation and silica features from soil; well-developed features formed in circulating pore water.

Above Pond-Sediment.

Plate 146 x 7500 Soil solution activity modifies precipitates more than in other environments sampled, clear features therefore a recent input into the drain from the soil.

Plate 147 x 4800 Aggregate of silica-cemented particles of considerable surface silica precipitation and solution; individual particles with silica surface precipitation.

Plate 148 x 4400 Aggregates above the pond incorporating some angular, recently input sediment.

Plate 149 x 2280 Strongly aggregated sediment with well-developed silica surface features.

Below-Pond Sediment.

Plate 150 x 3000 Aggregates with well-developed silica precipitation features; some individual fresh-faced and altered particles.

Plate 151 x 11600 Rounded individual fine particles with surface silica precipitation and solution features.

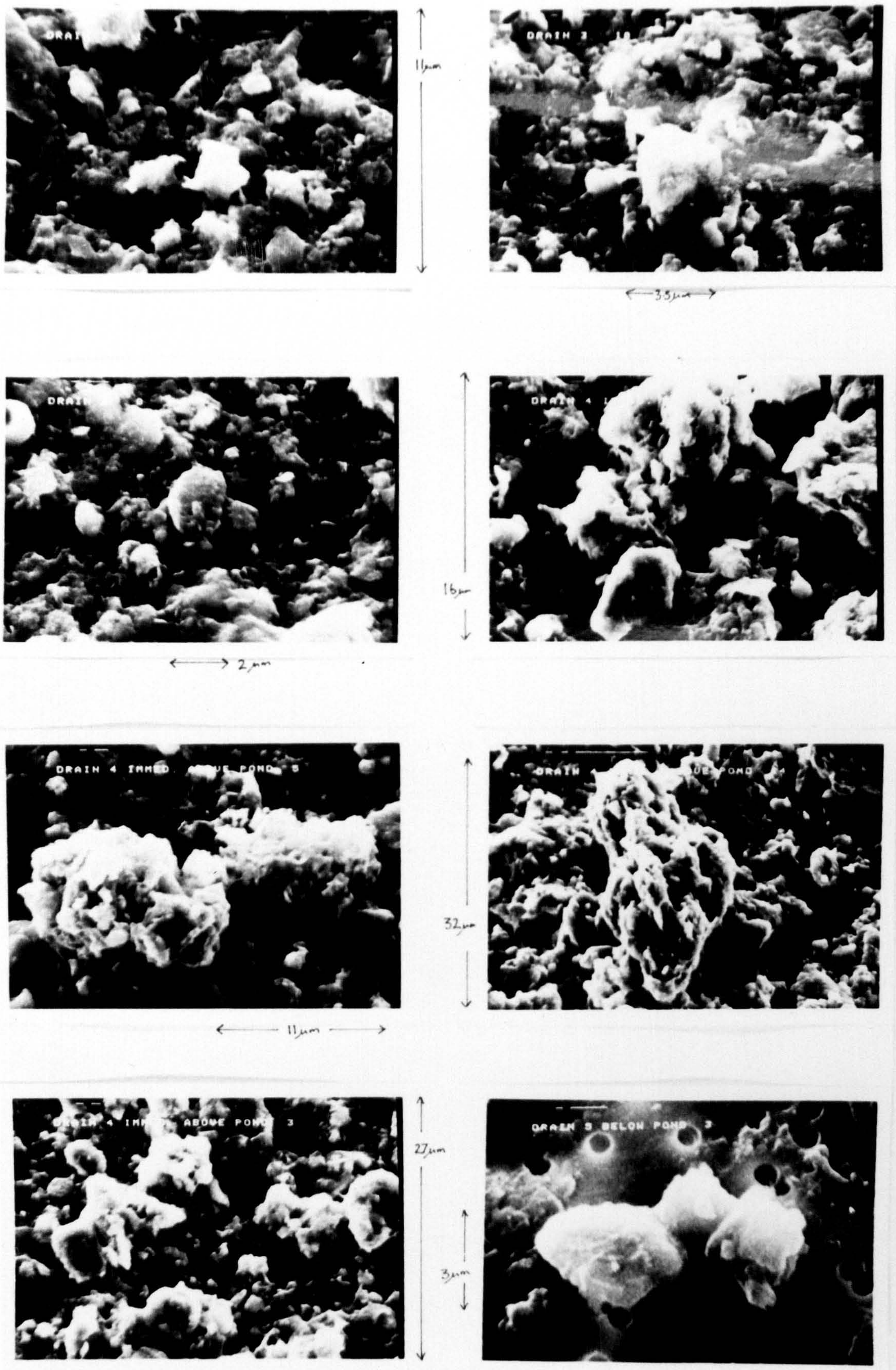

DRAIN 4 IMMED. ABOVE POND 5
DRAIN 5 BELOW POND 3
11μm
2μm
16μm
32μm
11μm
27μm
3μm

Plate 152 x 3300 Silica-coated particles with a little freshly input sediment including pollen grains.

Plate 153 x 3300 Individual particles with silica precipitates and small aggregates, after settling out of large aggregates.

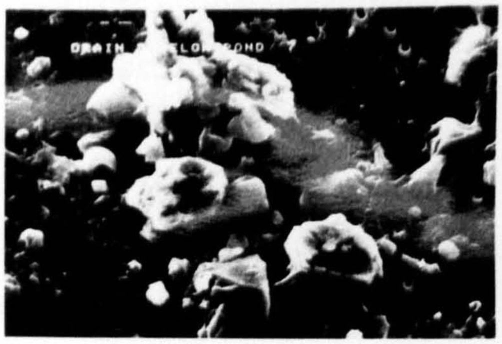
Sediment Below Main Sewer Junction.

Plate 154 x 760 Severely aggregated sediment with well-developed surface features of silica precipitation and solution.

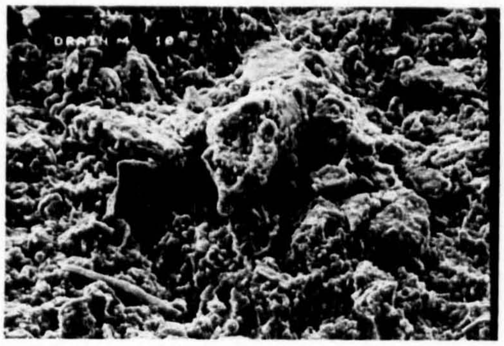
Plate 155 x 3500 Aggregated sediment with advanced silica precipitation and solution features.

Plate 156 x 2320 Aggregation and advanced precipitated silica coating.

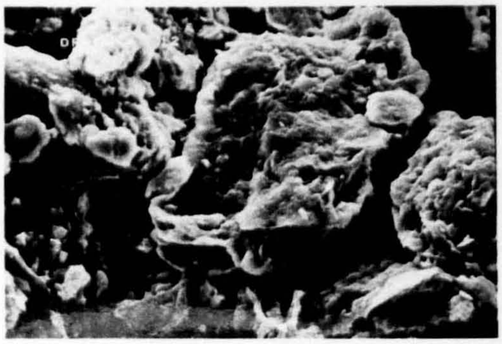
24μm.



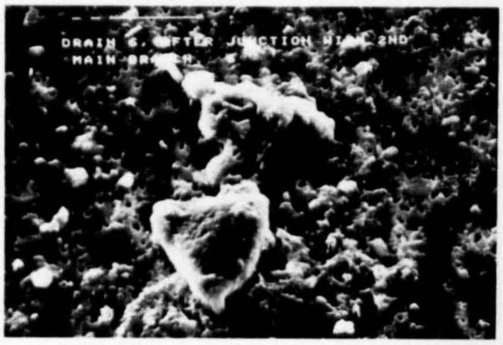
24μm



100μm



23μm



34μm

In conclusion, it can be seen that the process of aggregation of the sediment collected at the outfall occurs predominantly during drain transport. A small percentage of fresh material was observed through the system from the occurrence of impact features and angularity. Overall however, the sediment becomes progressively more rounded, and aggregated with an increasing development of silica precipitation and solution features, as the distance of transport increased downstream.. At the head of the catchment however, the results show a declining trend in the degree of development of aggregation with distance downstream but this can be explained by the influence of the high initial silica content and consequent aggregation, and the effect of the settling pond allowing the coarse aggregated material to settle out. Since the percentage aggregation results and the particle size data show trends of increasing aggregation and particle size downstream it seems highly probable that the trend in the degree of aggregation development would be reversed with an increased number of sample points along the system.

The method itself can be shown once more to be sufficiently sensitive for the aims of this drainflow study. Both the unexpectedly high silica results identified at the head of the catchment and the significant effect of the settling pond have been clearly demonstrated.

7.7. Graphical Analysis to Summarise Relationships Between Surface Textures.

At the end of this chapter in order to summarise the interrelationships of the surface textures, a selection of graphs are included showing the percentage of surface area covered by features on sediment from different sources.

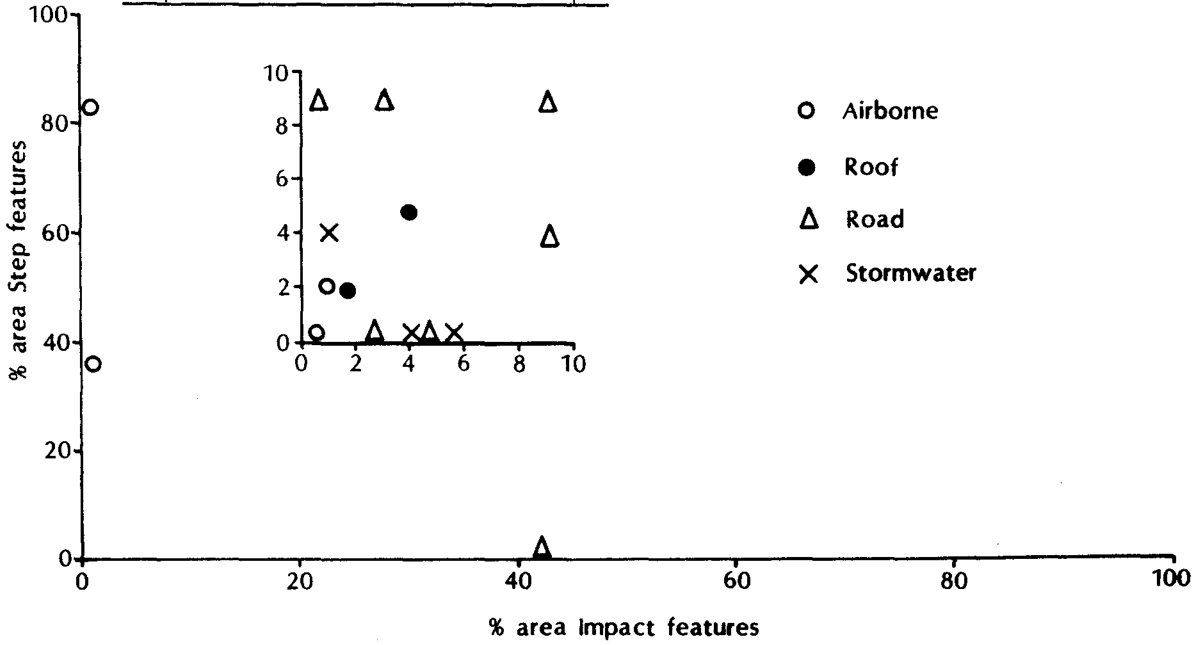
The relationships fall largely into three groups. The grain surface areas covered by features are positively correlated and those features occur together on a particle, when they have been formed under similar conditions. For example, the abrasion features: impacts pits and steps (Figure 7.1a); appear to increase together. However in this case both features may be brittle fracture phenomena (Field, 1971) which could account for the relationship. The relationship between the area of fresh face and impact pits is positive where both features are on fresh angular sediment and in the early stages of abrasion; shown by area 'a' in Figure 7.1b. The relationship is less positively correlated where faces are clean for example, those possibly resulting from cleavage plane breakage and erosion. Such a distribution is concentrated in area 'b' in Figure 7.1b. A further case might be expected where abrasion is so advanced as to have eroded the fresh face and this would fall in area 'c' of Figure 7.1.b. In this system the sediment does not reach this stage before particle surfaces become largely covered by precipitated silica.

A second type of relationship occurs between inversely correlated features, for example, fresh faces or impact surfaces

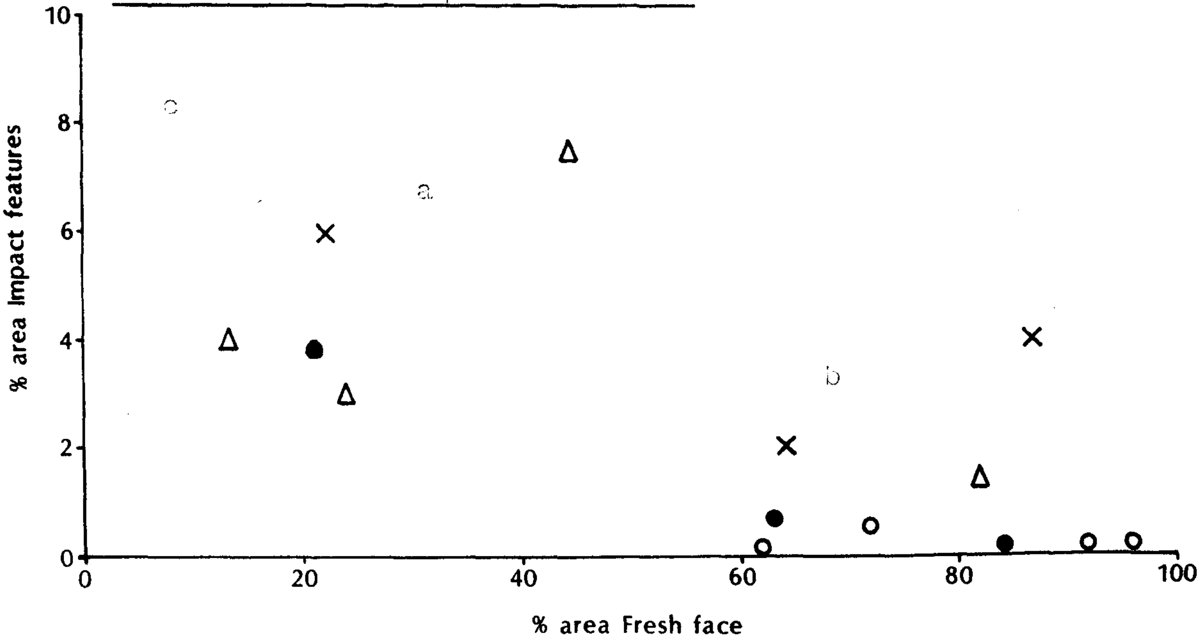
FIGURE 7.1.

PERCENTAGE AREA OF SURFACE FEATURES FOR ROAD, AIR, ROOF AND STORMWATER SEDIMENTS

(a) Impact Features vs. Steps



(b) Fresh Face vs. Impact Features



and those covered by precipitated crystallographic silica. Here the precipitate covers the particle surface and thus occurs at the expense of it (Figures 7.2a and 7.2b).

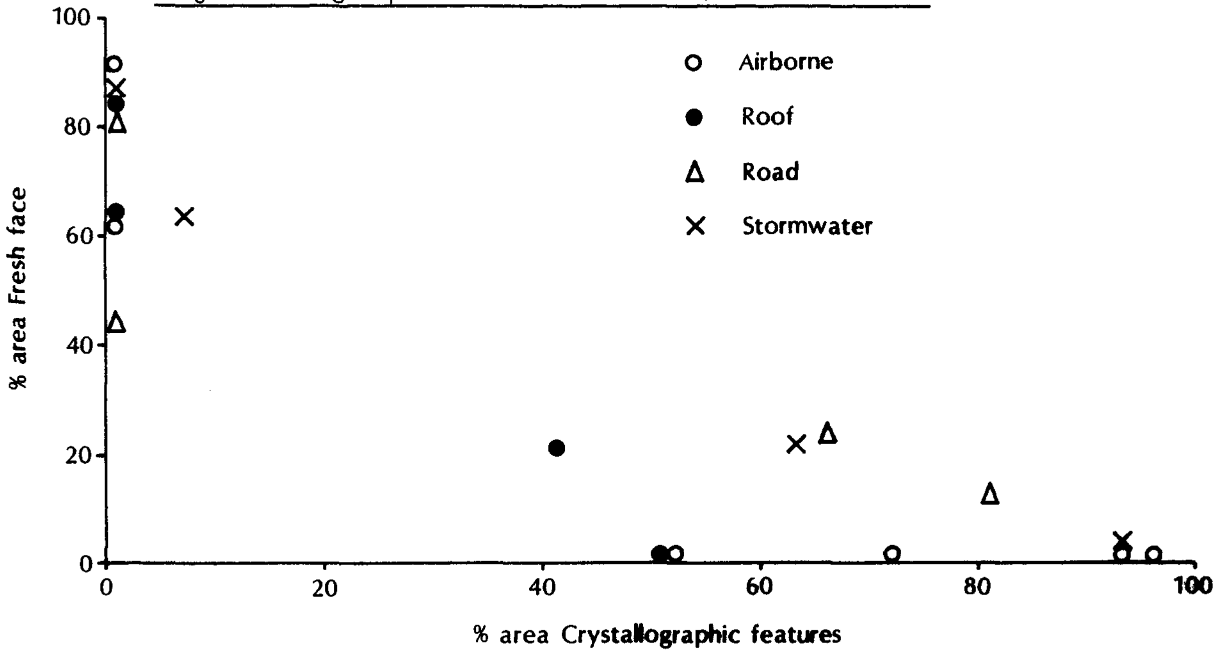
The third group, represented by Figure 7.3. of precipitated silica and upturned plates of spherical particles, demonstrates mutually exclusive features. Samples are clustered on either axis with neither type of particle exhibiting a feature of the other. An exception is shown by sample 'x' in this distribution which is an airborne spherical particle that survived drain transport and suffered abrasion and silica precipitation; and two roof sphericals 'y' and 'z' altered during a period in gutter runoff also lie outside the main distribution (Figure 7.3.).

The positively correlated results enhance the indentification of suites of features which occur together. The negatively correlated data illustrate the progressive change of one feature replacing another with time and distance of travel through the system. Finally, the mutually exclusive features demonstrate the different effects of transport in different media.

FIGURE 7.2.

PERCENTAGE AREA OF SURFACE FEATURES FOR ROAD, AIR, ROOF AND STORMWATER SEDIMENTS

(a) Crystallographic Features vs. Fresh Face



(b) Crystallographic Features vs. Impact Features

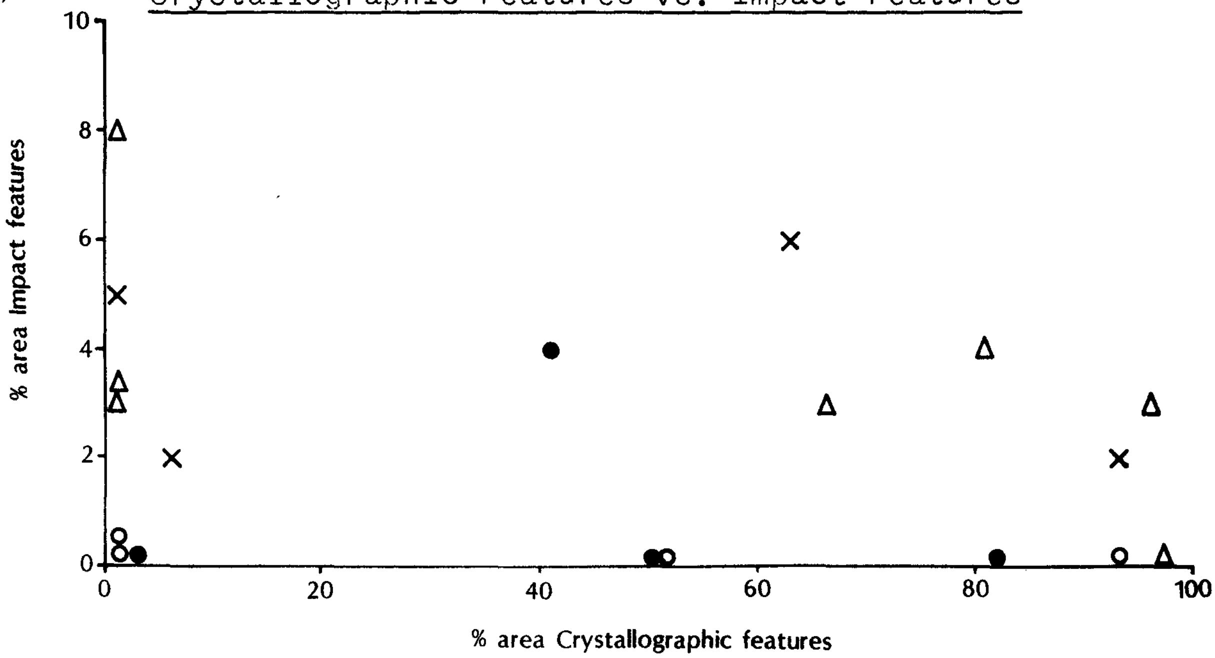
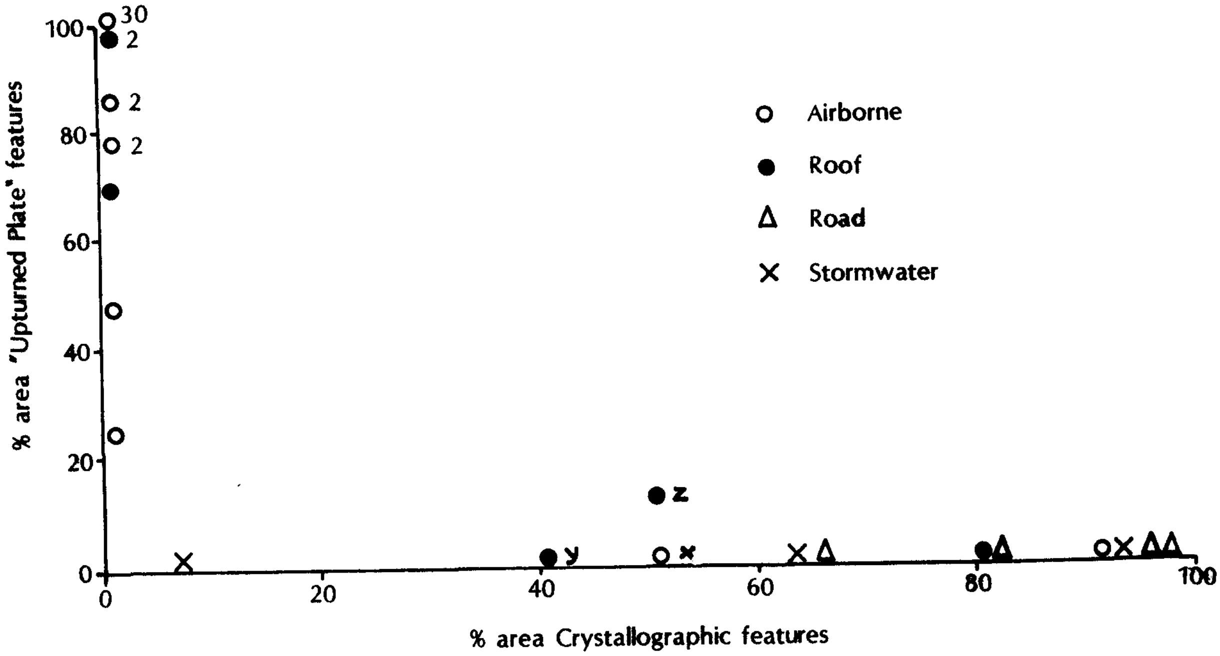


FIGURE 7.3.

PERCENTAGE AREA OF SURFACE FEATURES FOR ROAD, AIR, ROOF AND STORMWATER SEDIMENTS

Crystallographic Features vs. "Upturned Plate" Features



CHAPTER 8

SEDIMENT TEXTURE VARIATIONS DURING STORMFLOW.

8.1. Introduction and Fuzzy Data Analysis.

The main requirements of the particle size and surface texture analyses are to show the nature of the sediment and the way in which changes occur through the system. In the previous chapter the surface textures of the sediment were established for the major sources, for land use types and for those features attributed to transport in stormwater runoff. Further examination of the Fuzzy data classified by the same method in this chapter elucidates the changing dominance of sediment types during storms.

The study of changes in surface texture through storms is based on the examination of six storms, at least one from each storm Group and the mixed I/II type storm (see Chapter 3). Time and cost prohibited the examination of samples from every storm. In Chapter 10 the differences in surface texture between the four major storm types are studied in the context of hydrological conditions and sediment size patterns.

There is nothing particularly significant about the storms chosen; rather, they are as far as possible representative of their storm Group and have the fullest data sets. The storms of 16.11.81. and 17.11.81. are of special interest because they are consecutive with just less than 12 hours between the onset of the two storms. As a result of the known lag times between rainfall and discharge for each storm some estimates of transport times, and associated sediment alteration, may be deduced (see

Chapter 10).

The method of photomicrograph analysis described in Chapters 6 and 7 is applied here to the storm samples and the results are classified in order to aid the interpretation of surface texture variations during stormflow. The results discussed are presented as tables of means and percentage of the Fuzzy data. For approximately six storms samples, spread evenly through each storm, Fuzzy scores of three or more for each feature were drawn from the data. The features represented occurred repeatedly together in three distinct groups characterising the data thus: (i) aggregates, (ii) individual particles with surface silica precipitation and solution, and (iii) fresh-faced and abraded individual particles. In Table 8.2. the data for the first sample of storm 16.11.81. provide an example and the remainder of the data can be found in Appendix 7. The proportions of aggregates and individual particles were calculated as percentages and the results are shown on the graphs in the text.

8.2. Surface Textures in Storm Group I.

The discussion of the changing surface textures of the sediment sampled during the storms of Group I is based on the Fuzzy Analysis of micrographs of the storm 16.11.81. and with reference to the storm of 5.5.81. These storms are characterised by short durations and high initial rainfall intensities. The storm of 5.5.81 is mentioned here as it is the more typical and straightforward' in its rainfall and discharge pattern (Figure 3.2. whereas a minor renewal of rainfall intensity late in the storm of 16.11.81 slightly prolongs the duration of peak discharge (Figure 3.2.). However, as very little sediment was available during the storm of 5.5.81, the changes in surface texture are clearer through the storm of 16.11.81. It is the combination of a relatively short antecedent dry period of 56 hours and a preceding storm of type I or II which will have left

TABLE 8.1.

FUZZY ANALYSIS OF STORM SEDIMENT SAMPLES, 16.11.81.

Sample / Feature	2		5		8		11		14		17	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A Agregates ©	3.0	13	3.0	87**					1.8	14	2.0	26
B Si. Features	3.9	75*	3.4	70*	3.0	73*	2.9	95**	3.0	96**	3.4	87**
C Pitting	2.3	38	2.7	26	2.6	47	2.5	18	2.3	36	2.2	26
D Fresh Face	3.4	38	3.4	65	3.7	67	3.8	86**	3.4	64	3.0	83**
E Angularity	2.9	56	3.6	78*	3.5	53	3.6	77*	3.5	89**	3.4	78*
F Steps	2.2	38	2.7	57	2.0	47	1.9	73*	1.9	32	2.3	13
G Impact Pits	3.2	75*	2.7	65	2.5	73*	3.1	82**	2.8	86**	2.7	78*
H "Crinkles"												
I Clays			3.0	13	4.0	13	1.5	9	1.8	14	5.0	9
J. Sphericals							4.0	5				
K Flyash												

μ = Mean Fuzzy value of feature from sample particles

% = Percentage of particles with feature

71* = Notable values, 70-79

100** = High values, 80-100

© = Feature list given in Table 7.3

TABLE 8.2.

THE PRESENCE OF HIGH FUZZY SCORES FOR THE STORM OF 16.11.81.

SAMPLE 2.

Features	Particles		
Aggregates A	2a		
Si Sol*/ppt* B		5 6b 7a 7b 7c 8a 8b 8c 8d	
Fresh Face D		✓	1 2b 6a 8d 8c
Angularity E			✓ ✓ ✓ ✓ 4
Steps F		✓	✓
Impacts Pits G		✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓
	Aggregates	Individual particles with silica precipitation and solution.	Fresh faced or abraded individual particles, without silica precipitation.

the surface and the drain very largely clear of sediment before the onset of the storm of 5.5.81. The little sediment that may have been deposited in the drain will have aggregated during or at the end of the last storm in the low stormflow velocities of the decreasing discharge. The storm of 5.5.81 would then have rapidly cleared this drain sediment and any fresh individual surface sediment that had collected.

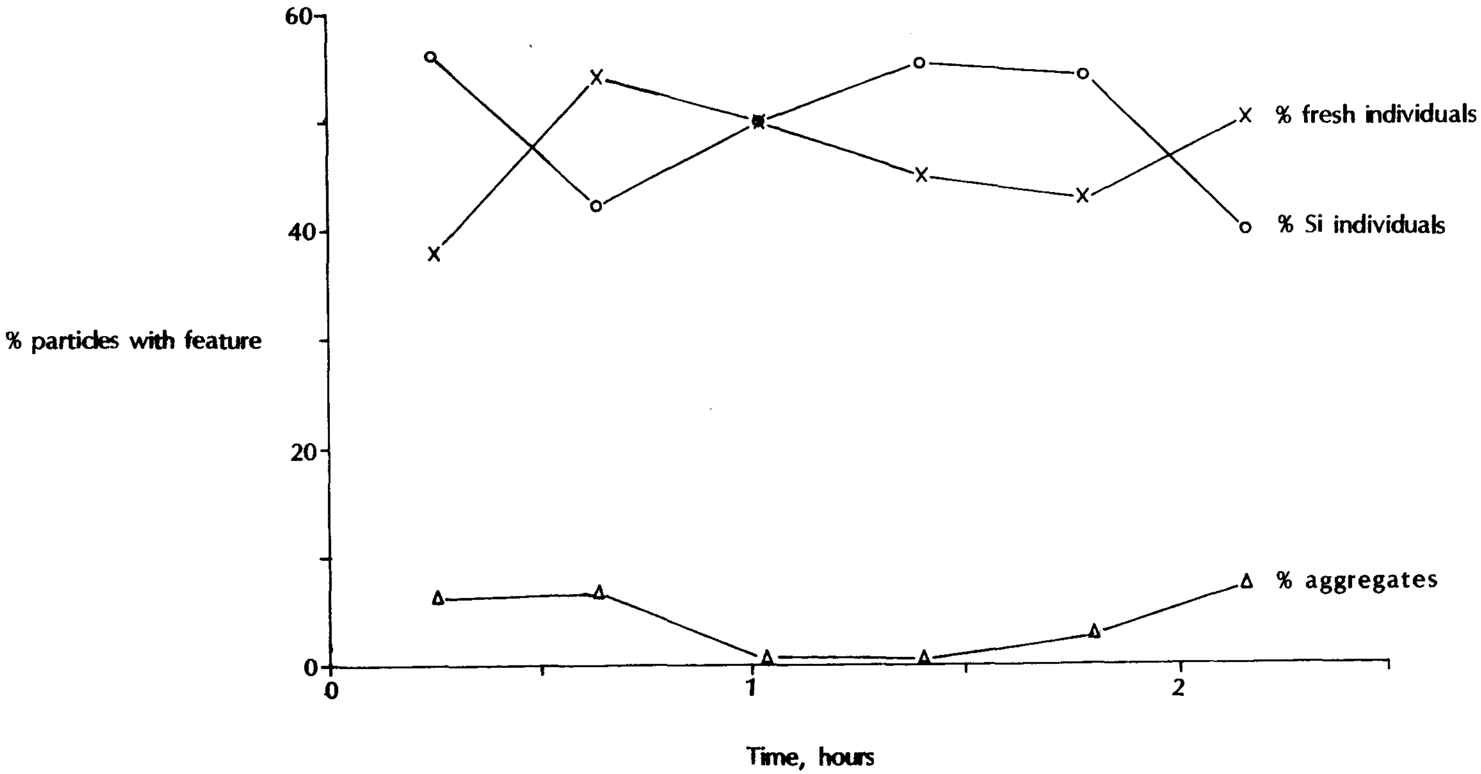
The storm of 16.11.81 had a significantly longer antecedent dry period of 398 hours during which a considerable amount of surface material will have accumulated and be readily available for entrainment in runoff. The preceding storm in this case was of Group III and had deposited some aggregated material in the drain which was collected in the early samples of the storm of 16.11.81. It can be seen from Figure 8.1 and Table 8.1 that the material deposited in the drain has undergone considerable silica precipitation and solution, and aggregation, (Plates 1 - 6) with Fuzzy scores of A, aggregates 3.0 and B, silica features 3.9 (Table 8.1). However this sediment was quickly removed with the onset of the next storm discharge and superseded by fresh-faced and abraded angular sediment (Plates 7-11). This sediment had been rapidly washed off the catchment surface and through the drain (Figure 8.1) as is shown by the presence of diatoms (Plate 11) and by the lack of precipitates. As the storm progressed the input of surface material decreased and individual particles began to show alteration both by abrasion and silica precipitation (Plates 12 - 16).

At this stage in most Group I storms once the peak discharge had been reached it would fall off quickly carrying almost all the sediment load with it. By the time the discharge had dropped to very low flows little sediment would be left in the system. That which does remain would be deposited and precipitation and aggregation would occur while moisture was available.

However, in the storm of 16.11.81 a slightly prolonged period

FIGURE 8.1.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 16.11.81.



STORM GROUP I.

Sediment Collected Early in the Storm of 16.11.81.
Comprising Drain Deposits of Previous Storm.

Plate 1 x 5900 Silica precipitation on and between particles from falling discharge of previous storm.

Plate 2 x 16000 Detail of Plate 1 showing silica precipitation and solution.

Plate 3 x 12000 Detail of Plate 1 showing silica precipitation over, and joining particles.

Plate 4 x 11000 Further example of overlying silica (→).

Plate 5 x 11900 Advanced silica precipitation attacked by solution processes.

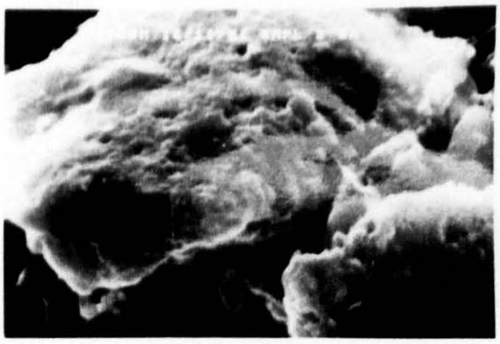
Plate 6 x 8700 Central particle affected by abrasion but minimal precipitation; possibly one of the first surface particles reaching the sampler, altered during long surface accumulation period.

Plate 7 x 3900 Overall view of some of the first surface sediment to reach the outfall; sample contains diatoms indicating rapid transport from the surface, slightly altered surface material, and isolated drain sediment remnants.

Plate 8 x 8800 A mixture of fresh-faced angular surface sediment and some precipitated silica features, e.g. central particle, remnants of drain sediment.

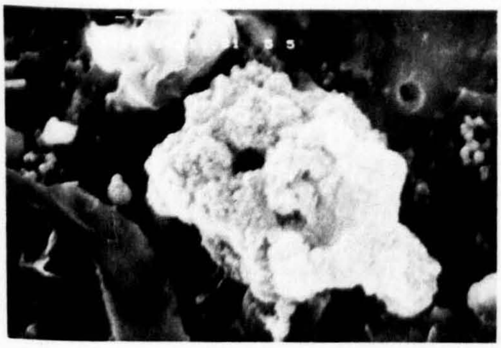
$13.5\mu m$

$5\mu m$



$6\mu m$

$7\mu m$



$6\mu m$

$7\mu m$

$9\mu m$

$3\mu m$

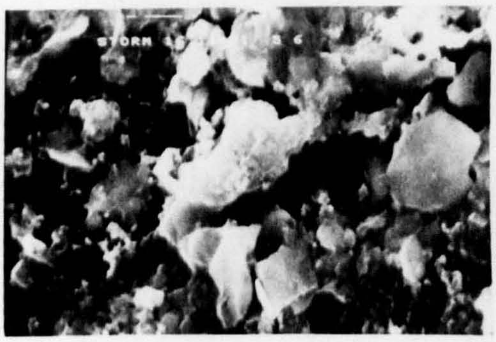


Plate 9 x 8900 Surface sediment, angular, abraded, precipitates most likely from previous drain transport; impact pits and hollows occur rounded by solution

Plate 10 x 12000 A fresh-faced and abraded sub-angular particle from the land surface, irregular edge from small scale step breaks and a few fine adhering particles; overall low particle surface relief.

Sediment Alteration.

Plate 11 x 5500 Diatom test: length = 17μm, intact and therefore recently transported from the surface; diatoms die without light and tests are rapidly broken by particle collisions.

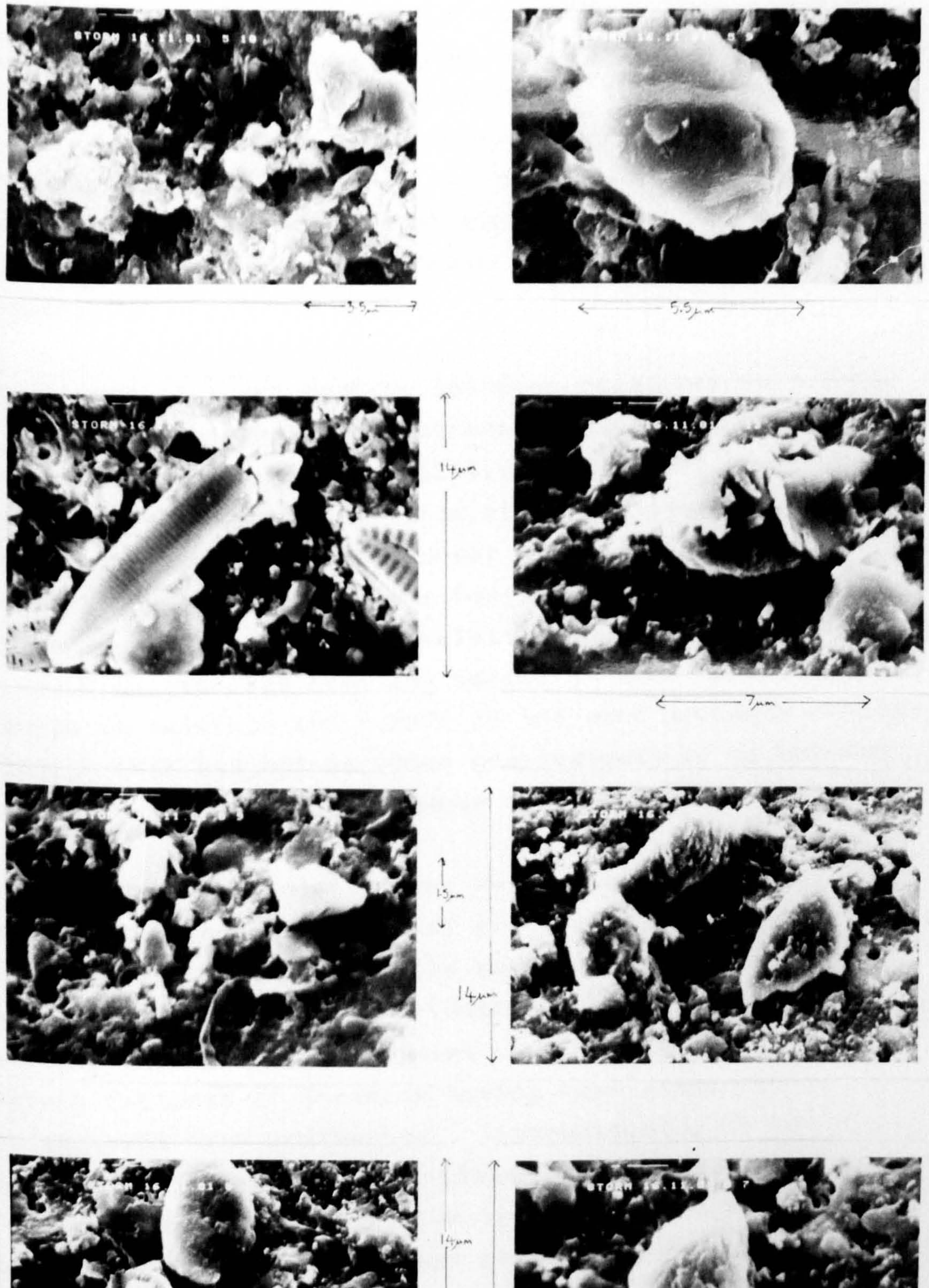
Plate12 x 9000 Abrasion possibly past its peak, angular, fresh-faced particle with earliest precipitation (lower right); steps and impact hollows (central particles.).

Plate 13 x 12100 Fresh, angular surface particles with transport abrasion hollows including impact hollows.

Plate 14 x 5900 Stages of precipitation: r.h.s. abraded particle with early precipitation and plastered particles; L.h.s. precipitation and solution in protected cavity; above, edge precipitates, slightly orientated, explanation unclear, possibly due to position in slipstream.

Plate 15 x 5900 Considerable silica coating but limited crystal growth, small scale solution hollows (top particle), more advanced solution (lower particle).

Plate 16 x 12100 Detail of early stages of crystal development (NB greater magnification than Plates 14 or 15).


3.5µm
5.5µm
14µm
7µm
1.5µm
14µm
14µm
6µm

of maximum discharge allowed time for more surface texture alteration than is usual for Group I storms (Plates 17-24). This sediment then appears to be flushed out followed by a decrease in discharge which is, however, short-lived. There is evidence at this point of a small-scale renewed input of fresh material from the surface (Plates 25-31), which is confirmed by the occurrence of diatoms (Plate 32). The last few samples of the discharge therefore show a range of sediment textures from fresh features to aggregates (Plates 32-41).

The renewed input of fresh surface sediment may be due to a local surge in runoff somewhere in the catchment. There is evidence from other urban drainage systems (Ellis, 1976, 1977, 1982; Adams and Pratt, 1981) describing sediment from different areas joining the falling discharge at both different times and different rates. A minor delay in the discharge is a further explanation but in that case an increase in silica precipitation rather than abrasion features would be expected from the period in slow moving water. A local surge in rainfall and runoff is the most probable explanation although this can not be shown conclusively if it occured beyond the range of the rainfall gauge (Colyer, 1981).

Once a storm has removed most of the surface sediment renewed rainfall runoff may entrain material previously protected by accumulated sediment, for example in road surface crevices, and thus inaccessible to early runoff (Gutt and Nixon, 1972). It is questionable whether such sediment can be expected to have more distinct features of abrasion having been protected by overlying sediment from weathering. Alternatively, it could be argued that any water would gravitate to these places and provide conditions for precipitation and solution features to develop. From Table 8.1 much higher percentages of well-developed impact features (D-G) can be seen for the renewed input of surface sediment than were measured on the first sediment input. This suggests that either the sediment had remained protected; or it was coming from a different source area where rainfall was now occurring; or it was being freshly eroded. Any of these

Further Alteration of Sediment, Storm 16.11.81.

Plate 17 x 2700 Overall view, slightly more advanced alteration by abrasion and precipitation; particles remain separate at this stage.

Plate 18 x 9100 More abrasion features than hitherto; irregular surface impact pits, steps, fresh faces and straight edges; clays, possibly kaolinite (→).

Plate 19 x 4000 Abraded particle with minimal precipitation, thus recently transported from the surface, cf. moderately well-developed precipitates on nearby particles.

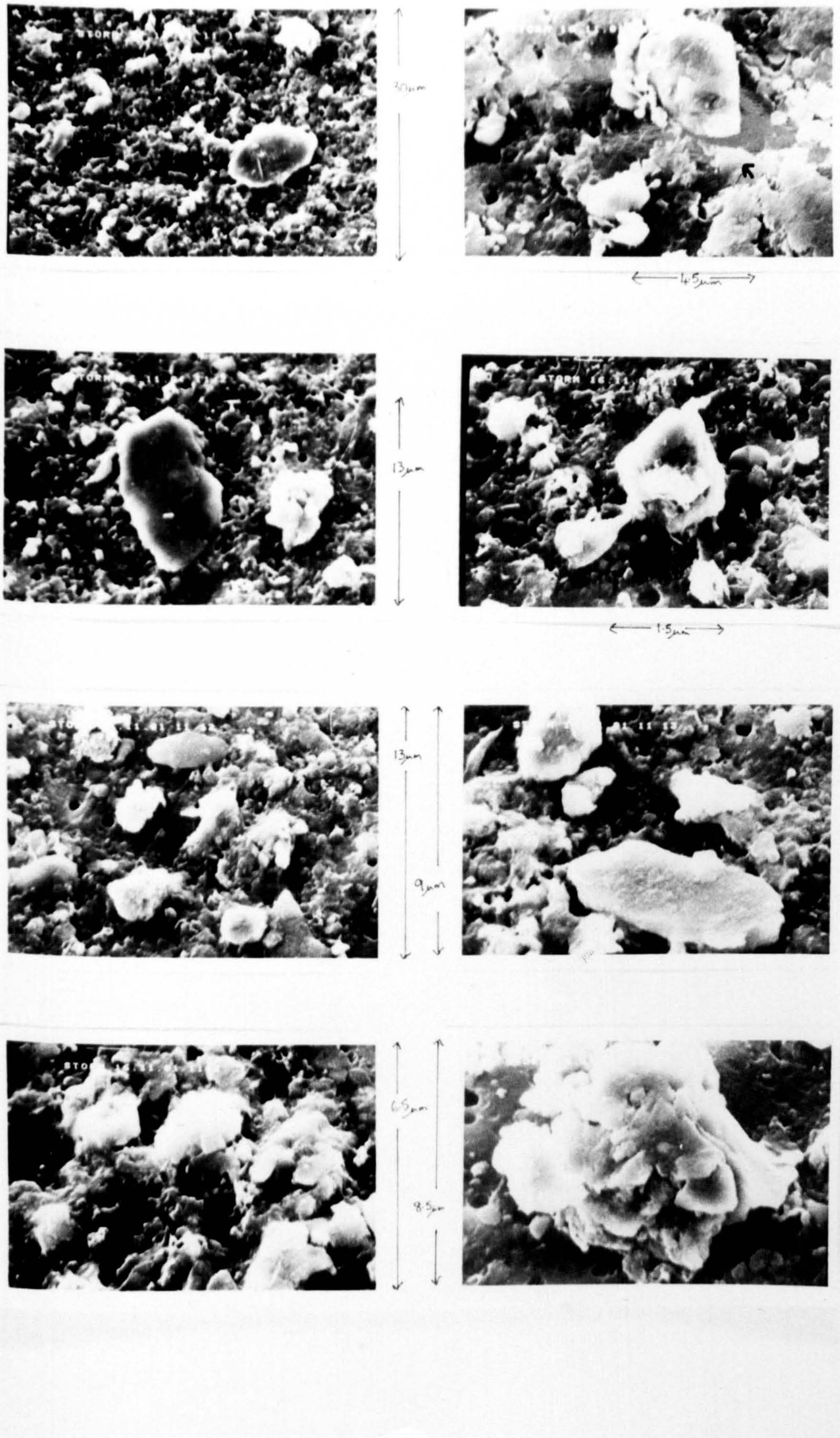
Plate 20 x 9000 Increased silica growth in particle cavity and early stages of silica linking particles.

Plate 21 x 6000 Widespread silica growth on individual particles and early stages of aggregation.

Plate 22 x 9100 L.h.s. silica cementation between particles; r.h.s. advanced silica growth.

Plate 23 x 12200 Particle aggregation and silica cementation between particles.

Plate 24 x 9100 A small aggregate, well-cemented, probably transported intact in this form; fresh-faced angular particles with impact pits and solution hollows.


30µm
4.5µm
13µm
1.5µm
13µm
9µm
6.5µm
8.5µm

Renewed Fresh Sediment Input, Storm 16.11.81.

Plate 25 x 2700 Fresh-faced, angular, individual particle with surrounding fine individuals; minimal silica precipitation, well-defined straight steps. (→).

Plate 26 x 12100 Predominantly fresh-faced, angular individual particles.

Plate 27 x 9100 Predominantly fresh surface material with minimal remains of silica development.

Plate 28 x 8200 A group of angular individual particles but no signs of silica structures such as cementation as seen in Plates 17-24; fine particles with solution hollows; overall low relief (< 0.24μm).

Plate 29 x 12100 Angular individual particles amongst minor silica remains; upper particle appears to have cracks enlarged by solution.

Plate 30 x 9000 Abrasion features from impact during rapid, renewed transport surge.

Varied Late- Storm Sediment.

Plate 31 x 9000 Some renewed silica development as renewed discharge decreases, an indication of the great rapidity of silica development as soon as the flow allows.

Plate 32 x 6100 Diatom, indicating fresh sediment input.

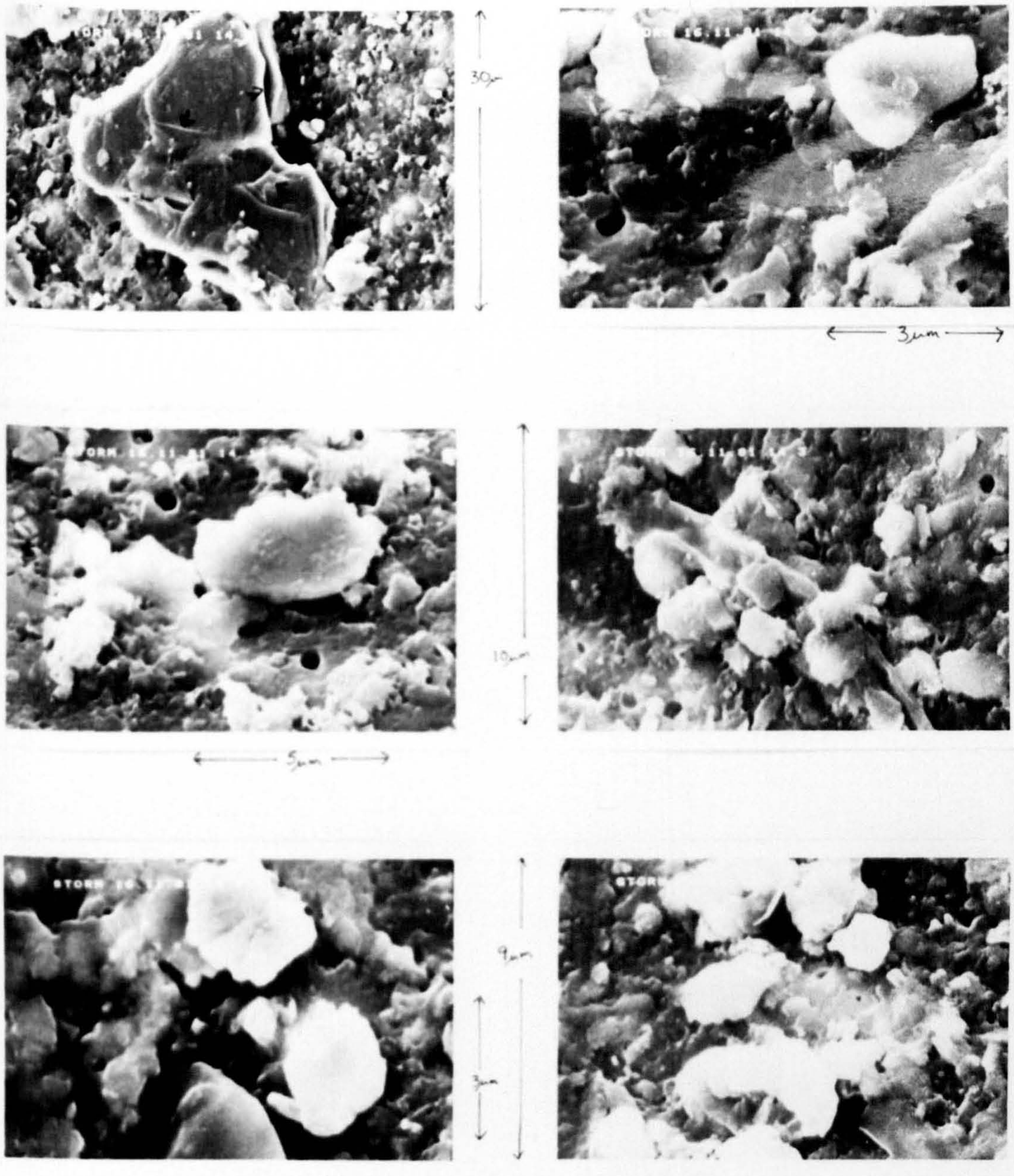

30µm
3µm
5µm
10µm
9µm
3µm
3µm
9µm
13µm

Plate 33 x 12300 Fresh angular surface sediment; first silica precipitates on particle (lower centre).

Plate 34 x 9100 Particle with early renewed silica precipitation.

Plate 35 x 9200 Particle clustering and interparticle cementation ie. early aggregation processes.

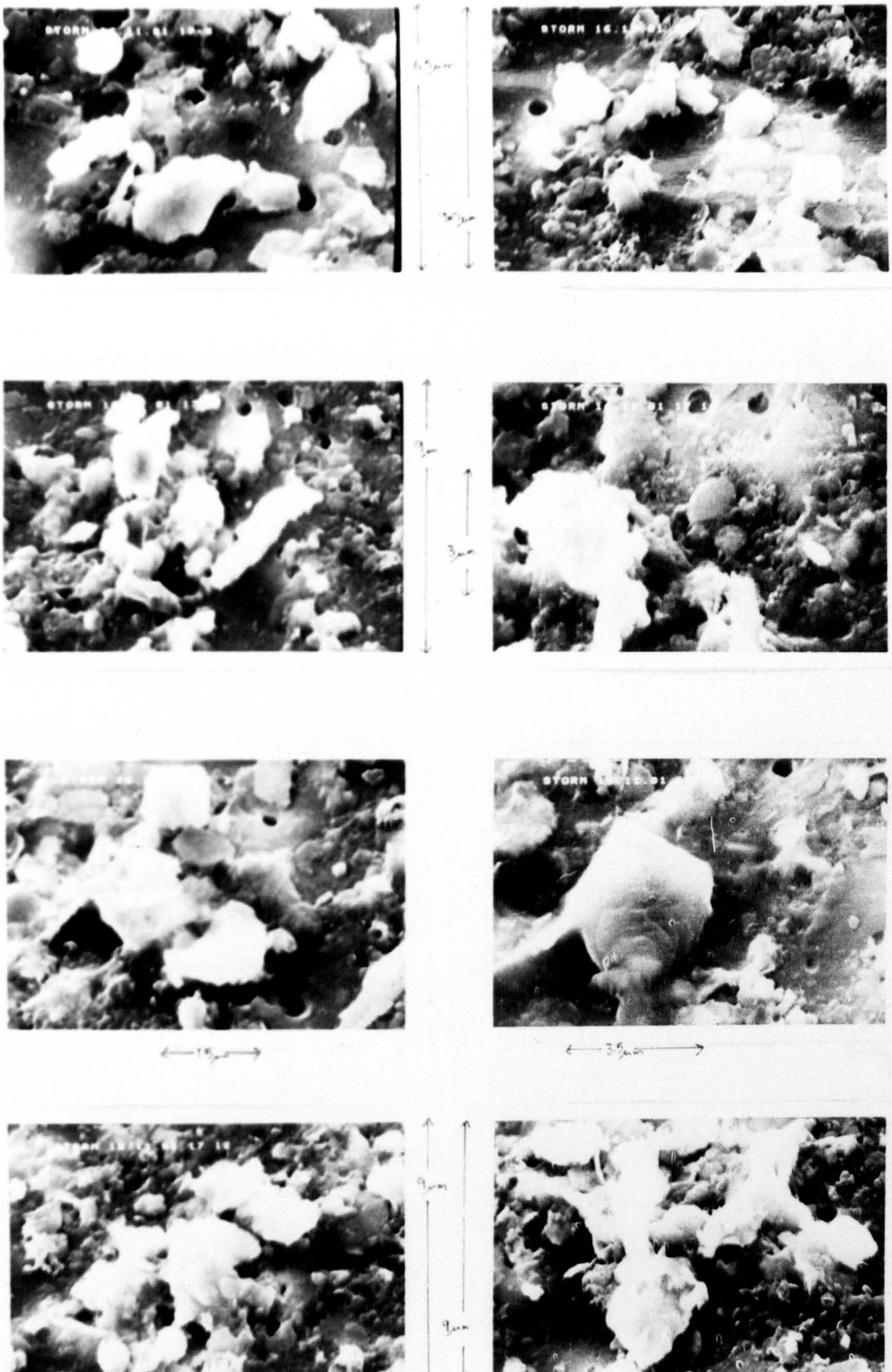
Plate 36 x 12400 Silica precipitation amongst particles.

Plate 37 x 12300 Particle clustering and silica cementation; broken diatom test (→) indicates longer transport period than for whole tests; little new sediment now entrained, surface clear and rainfall ceasing.

Plate 38 x 12400 Relatively well-developed silica precipitates on individual particles.

Plate 39 x 9200 Particle clustering; diatom fragment.

Plate 40 x 9100 Early aggregation of particles in various stages of abrasion and precipitation development.


3μm
15μm
35μm
9μm
9μm

<u>Plate 41</u> x 9200 Further example of early aggregate formation


9μm

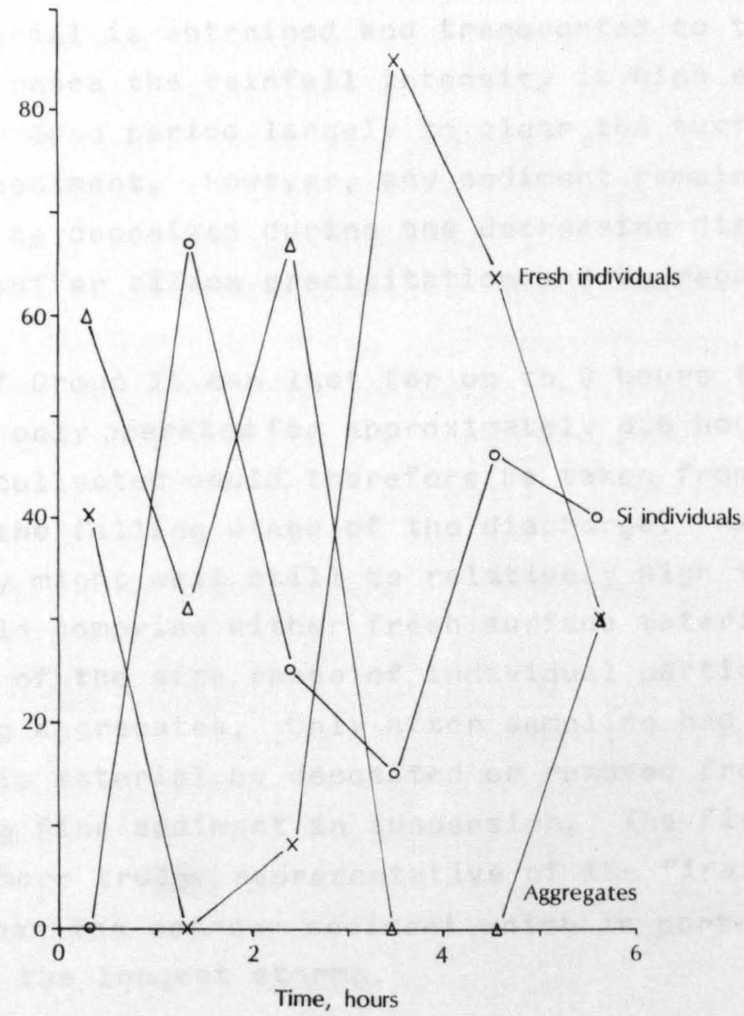
explanations would fit in with the summarised local resurgence in rainfall described above. Certainly it seems in this case that rapid surface drying prevented noticeable widespread silica precipitation.

The only significant difference between the two Group I storms results from their different antecedent conditions. The major input of fresh surface sediment in the storm of 5.5.81, with an antecedent dry period of 56 hours, comes approximately half way through the storm. In contrast, fresh sediment is prevalent nearer the beginning of the storm of 16.11.81. when the 398 antecedent dry hours provided accumulation time for large quantities of surface sediment. The relatively short dry period preceding the storm of 5.5.81 appears to be too brief for the accumulation of substantial quantities of surface sediment around the sampling point. However, it is believed that surface sediment is being continuously deposited and makes up 40% of the first sediment reaching the outfall during the storm of 5.5.81 (Figure 8.2). Most of the sediment in this case was probably entrained from areas of the catchment further from the sewer input points beyond the reach of the preceding scouring rainfall. The distance of transport from the further points of the catchment accounts for the delay in the arrival time of the fresh sediment at the outfall.

To summarise, storms of Group I, having cleared the drain of previously deposited sediment, are characterised by the early input of sediment from the land surface with the initial high rainfall intensity and associated high entrainment capacity. The proportion of fresh sediment input gradually decreased and after approximately 1 to 1.5 hours, or less in storms of shorter duration, silica precipitation and aggregation processes resume during the ensuing period of falling discharge.

FIGURE 8.2.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 15.5.81.



8.3. Surface Textures in Storm Group II.

The storms of Group II are characterised by their relatively long duration and high total rainfall. The rainfall builds up to peak intensity in the middle of the storm then decreases again at a similar rate. Generally, the first sediment moved to the outfall is the drain material deposited by the previous storms and is in an aggregated form with features of silica precipitation and solution. As the rainfall intensity increases fresh surface material is entrained and transported to the outfall. In many cases the rainfall intensity is high enough for a sufficiently long period largely to clear the surface and the drain of sediment. However, any sediment remaining in the drain will be deposited during the decreasing discharge and subsequently suffer silica precipitation and aggregation.

Although storms of Group II can last for up to 9 hours the automatic sampler only operated for approximately 6.5 hours. The last samples collected would therefore be taken from just the beginning of the falling stage of the discharge. As the discharge capacity might well still be relatively high the sediment load would comprise either fresh surface material at the larger end of the size range of individual particles, or freshly-forming aggregates. Only after sampling had finished would this material be deposited or removed from the system leaving fine sediment in suspension. The fine sediment is thus more truly representative of the final stages of these storms than the coarser sediment which is portrayed in the results of the longest storms.

The storm of 10.10.80 is representative of Group II (Figure 8.8.) The rainfall lasted 8.5 hours and generated a total of 9.1mm. The preceding significant storm was of type I which by itself would be expected to leave little or no sediment in the drain. However, the antecedent dry period was interrupted by short, light rainfall which might have provided enough moisture for silica precipitation on any surface-or drain-sediment but which was insufficient to activate the sampler.

Aggregates dominate the sediment sampled early in the storm with a value of 100% in Sample 15 and unusually high Fuzzy scores of 4 in both Samples 7 and 15 (see Table 8.3, Figure 8.3 and Plates 43-45) The high degree of development of the aggregates points to their having formed in the steady moist conditions of slow moving or stationary flow in the drain. The majority of individual particles carrying precipitated silica appear to have been incorporated into the aggregates. Fresh material is introduced into the drain in the early and middle stages of the storm (Plates 46-50). However, the velocity is still relatively low and allows time for substantial silica precipitation and abrasion to alter the sediment over the following 2 to 4 hours, as shown in Plates 51-55. An increase late in the storm of fresh material and precipitate-covered individual particles (Plates 56-60) corresponds with a short period of increased rainfall intensity. The renewed discharge carried fresh sediment into the drain as well as the sediment already undergoing silica precipitation in surface runoff and lying water.

As described above, although falling, the discharge is still sufficiently high at the end of the sampling period to transport relatively coarse sediment (Plates 61-67). Figure 8.3 demonstrates the situation clearly when at sample 47 the sediment comprises:

- 50% individual precipitated particles
- 30% fresh individual particles
- 17% aggregates in early stages of development.

The sediment transported by Group II storms is therefore characterised by particles predominantly exhibiting silica precipitation features throughout the storm. Fresh sediment input between early and mid-storm is rapidly altered by silica

TABLE 7.3.

FUZZY ANALYSIS OF STORM SEDIMENT SAMPLES, 10.10.80.

Sample Feature	7		15		23		31		39		47	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A @	4.0	72*	4.0	100**	4.2	64	4.9	73*	4.9	53	3.0	32
B	3.5	100**	4.3	100**	3.5	93**	3.8	100**	3.7	80**	3.3	90**
C	3.5	54	3.0	100**	2.9	79*	3.8	82**	3.9	60	3.7	37
D	3.4	44	2.0	67	1.9	79*	2.8	46	3.1	73*	2.9	84**
E	3.4	44	3.0	33	2.1	71*	2.8	46	3.1	80**	3.0	68
F	2.5	26	2.0	33	2.3	21	2.0	18	1.5	5	3.2	26
G	2.2	28	1.5	67	3.1	71*	3.2	46	4.0	23	3.6	74*
H							1.0	9				
I									4.0	5		
J	1.0	5	1.0	33	1.0	7	1.0	27	1.0	5	1.0	16

μ = Mean Fuzzy values of feature from sample particle.

% = Percentage of particles with feature.

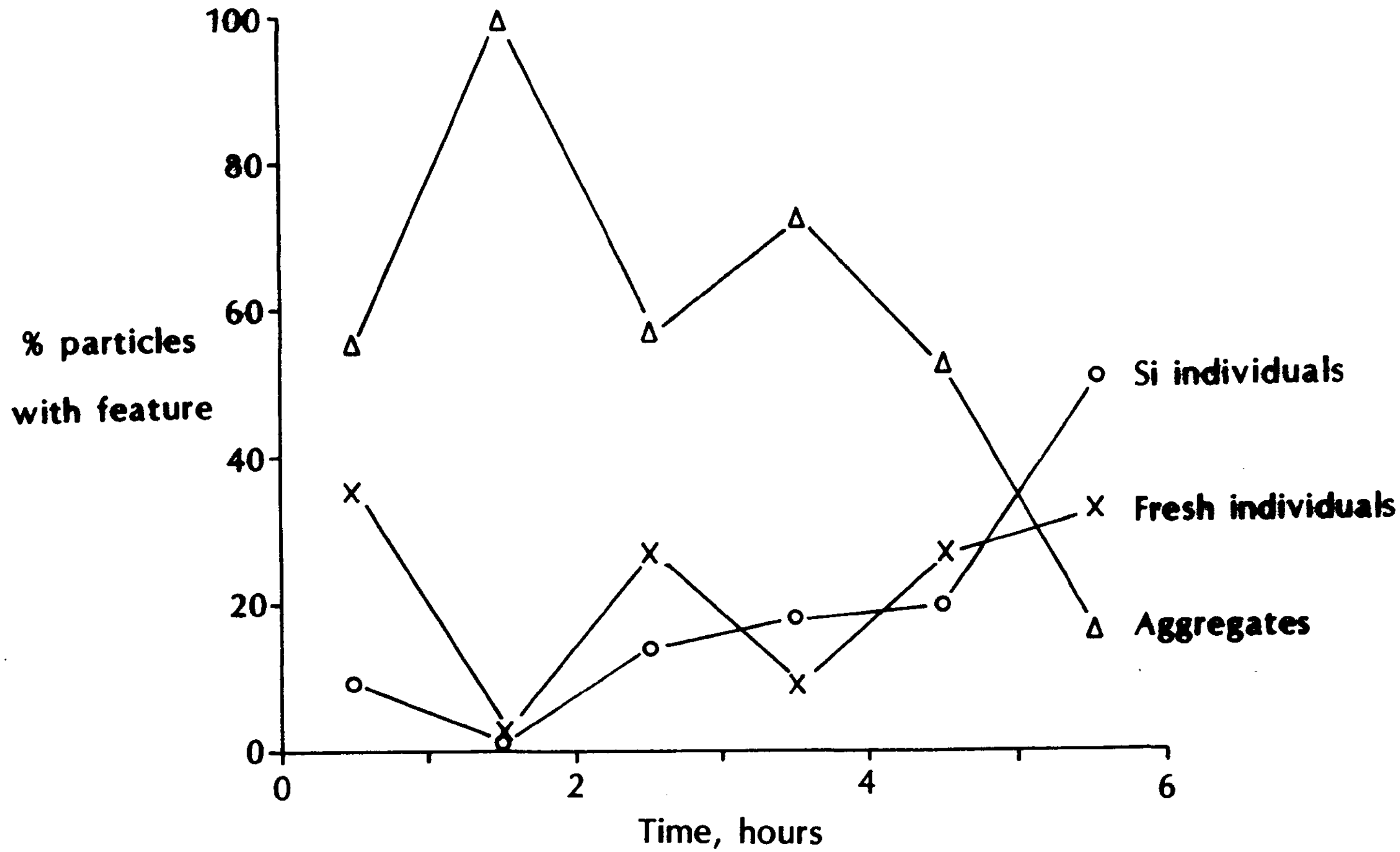
71* = Notable values 70-79

100** = High values 80-100.

@ = *Feature list given in Table 7.3*

FIGURE 8.3.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 10.10.80.



STORM GROUP II.

Storm 10.10.80. Early Samples of Aggregates from Last Storm.

Plate 42 x 860 Well-developed aggregate and surface silica precipitation and solution features.

Plate 43 x 860 Aggregate and occasional fresh, fine angular fragments and broken diatom test indicating slow moving fresh material and aggregates reaching outfall first.

Plate 44 x 1190 Aggregate with silica precipitation, large individual or aggregated particle (low, centre), silica-coated and a few fine fresh individual particles. NB. little change in samples during first 2 hours of storm.

Plate 45 x 890 Aggregates and individual particles, some fresh and some silica coated.

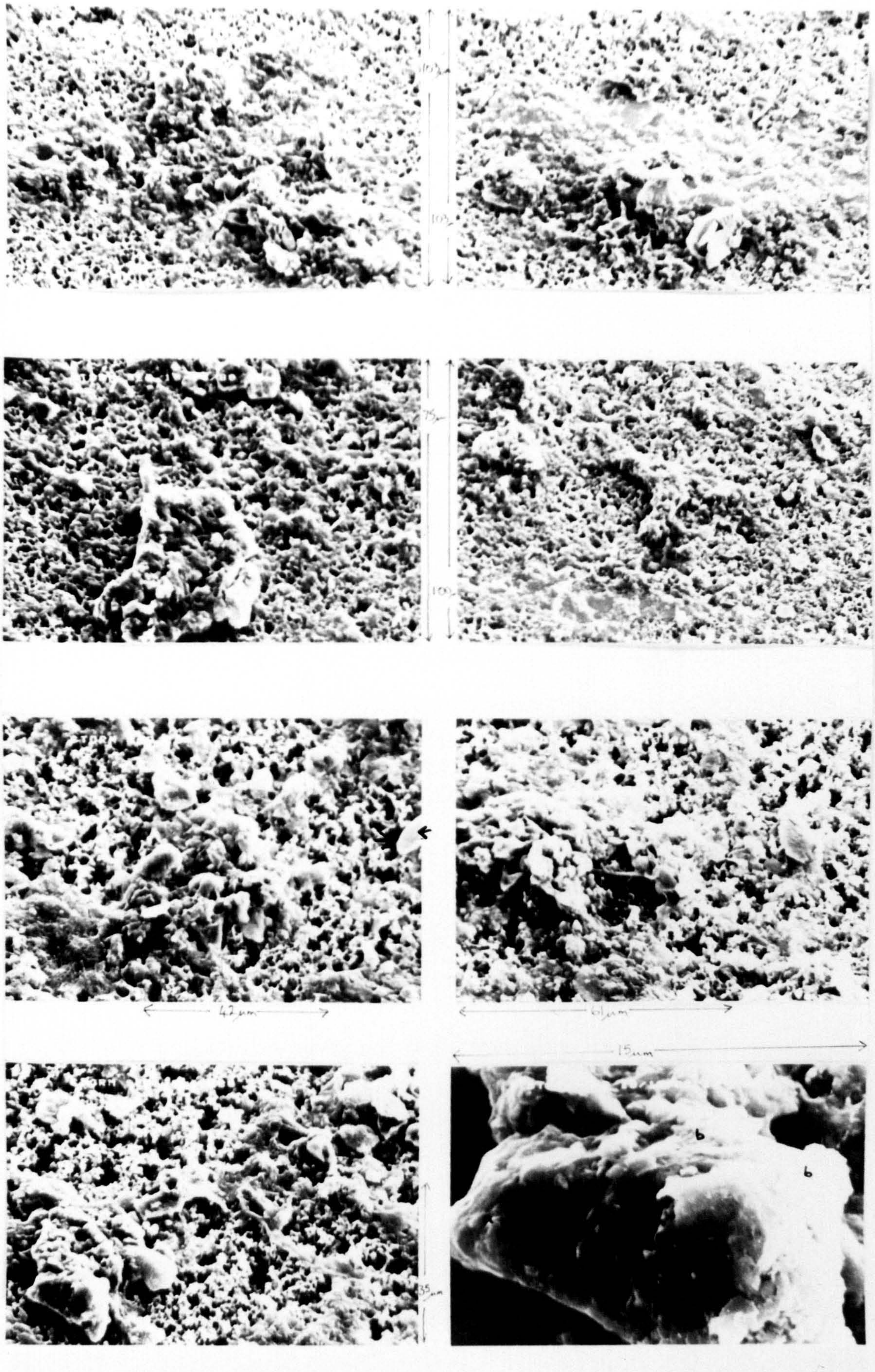
Fresh Material Reaching Outfall Early and Mid-Storm.

Plate 46 x 1400 After approximately one third of the storm duration fresh material occurs in substantial quantities; diatom (→) indicates recent sediment cf rapid through-put and alteration of Group I storms.

Plate 47 x 1400 Fine, fresh, individual particles amongst aggregates.

Plate 48 x 1500 Aggregates and silica-altered individuals with a few fresh, angular and abraded particles; noticeable solution of thin silica coatings.

Plate 49 x 8700 Detail of Plate 48, abraded face (a) with impact and solution hollows, rounded projections (b) and fine, adhering angular fragments; r.h.s. face shows silica precipitation.


42μm
61μm
15μm
b
b
35μm

Further Altered Aggregates and Fresh Material.

Plate 50 x 2600 Relatively fresh material but impact pits, solution hollows and silica precipitation are present; particles clustering and possibly cemented together.

Plate 51 x 1140 Overall view of aggregates and fine, fresh, angular, individual particles (a), many with silica precipitation (b).

Plate 52 x 1500 Fresh, angular and silica-altered particles in early stages of aggregation; conchoidal steps, from transport of parent material (centre particle); advancing silica coating with small solution hollows (→a,b)

Plate 53 x 1500 Individual particles, abraded and with early silica growth indicating alteration occurring during slow drain transport.

Plate 54 x 2700 Relatively fine, fresh sediment, abraded and with silica precipitation being incorporated into the aggregate probably from the previous storm.

Plate 55 x 3800 Well-developed silica precipitation features forming a new aggregate (noticeably less substantial than the aggregate in Plate 54).

Renewed Input of Fresh Sediment.

Plate 56 x 1500 Freshly input individual particles, some altered by abrasion and silica development; recent input confirmed by presence of diatom test.

Plate 57 x 1500 Fine fresh particles on old aggregate; spherical particles also indicates freshly input particles to some extent as they rarely survive drain transport.

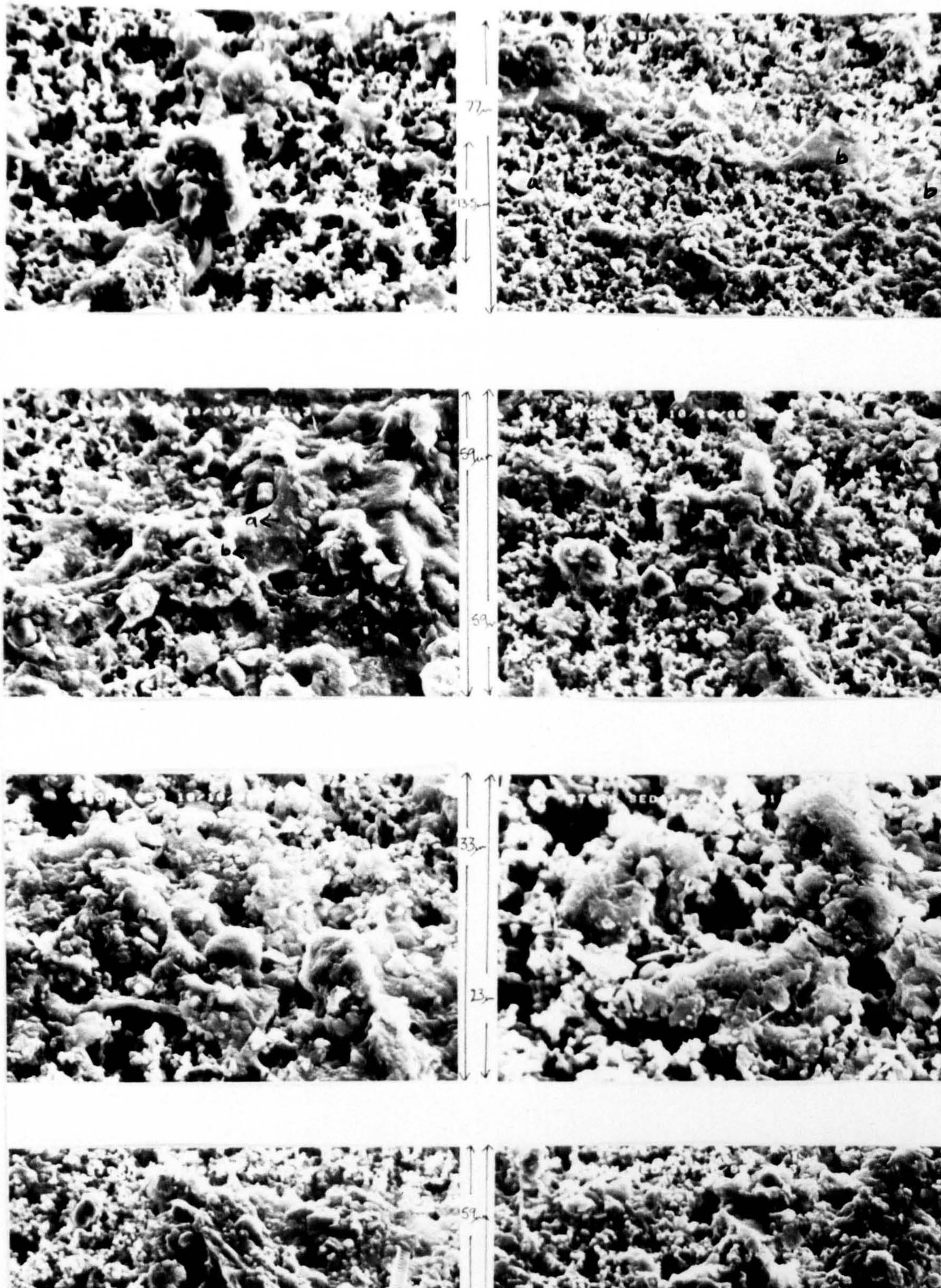

77μm
13.5μm
a
b
b
a<
b
59μm
59μm
33μm
23μm
59μm
59μm

Plate 58 x 1500 Fresh, angular, abraded particles with early silica precipitation amongst aggregates; silica growth in abraded hollows (particle far left).

Plate 59 x 4000 Angular, individual particles, altered by abrasion and silica activity and being incorporated into an aggregate; pitting in particle surface and solution of precipitate (lower left).

Coarse Sediment Carried in Last Sample Monitored.

Plate 60 x 2700 Fresh, angular sediment; fresh faces abraded with step features and impact pits; silica precipitation with adhering particles being incorporated into aggregates.

Plate 61 x 5700 Fine, individual particles: fresh faces (a); edge abrasion features (b); thin silica precipitates on faces, attacked by solution. Note: Sampling period ended after only 75% discharge duration.

Plate 62 x 1180 Clustered diatom tests largely undamaged; precipitated silica appears to be cementing them together and incorporating pollen grains and a few particles.

Plate 63 x 5700 Relatively fresh particles being incorporated into an aggregate.

Plate 64 x 5700 Abraded, sub-angular, relatively fresh particles and areas of early silica precipitation; impact pits and irregular broken surfaces rounded off by solution and further abrasion.

Plate 65 x 2700 An aggregate comprising many relatively fresh-faced particles and therefore likely to have been formed recently.

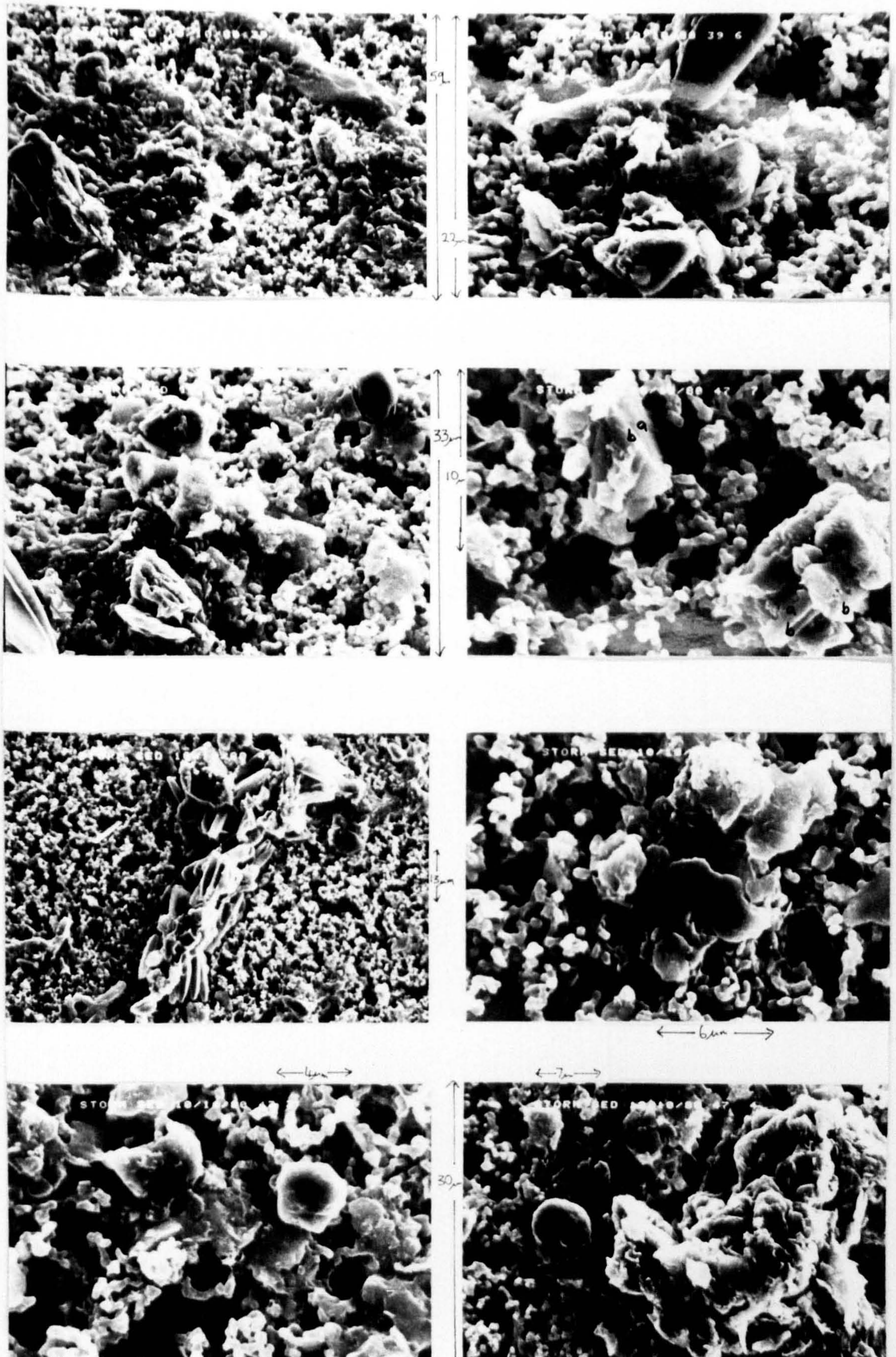
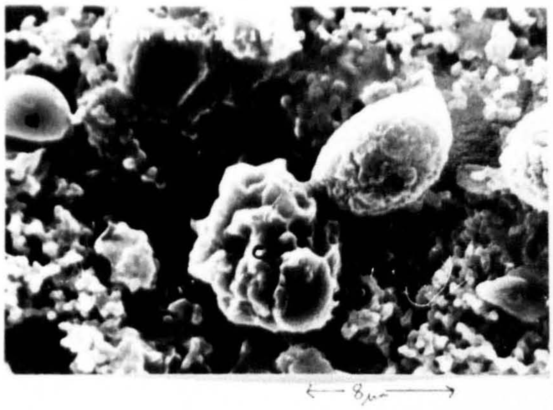

22μm
33μm
10μm
6μm
4μm
7μm
30μm

Plate 66 x 3900 A range of particles including rounded fresh-face with early silica precipitation (a) and angular fresh-face with impact pits and cleavage breaks (top left); convoluted fungus (b); a form of silica (c)

Plate 67 x 1500 Well-develoed precipitation and aggregate but still evidence of fresh particles (→); freshness of aggregate components and thin nature of precipitate suggests newly forming aggregate compared with predominance of old ones shown above.


8μm


58μm

activity. The strong similarity in the appearance of sediment sampled throughout these long storms confirms that it is derived from one major source; the road surface. Rapid through-flow is once again confirmed by the presence of diatoms amongst this storm sediment.

8.4. Surface Textures of Mixed Storm Grouping I and II.

The storm of 17.11.81 illustrates sediment features of both the storm Groups I and II. After initial high intensity rainfall typical of storm Group I, renewed rainfall from 2 to 6 hours prolonged the storm and discharge duration and generated sediment characteristics of Group II storms (Figure 8.3).

The rainfall of the storm of 17.11.81 began just 11.5 hours after the end of the storm of the 16.11.81 (cited as the Group I example above). Group I storms leave the drain clear of sediment but the slightly slower falling of the discharge than is usual allowed for a little sediment deposition and indeed for silica precipitation and the preliminary development of aggregates. That sediment is now seen in the first few samples of the storm of 17.11.81 (Plates 68-73). The dominance of individual particles with silica precipitation in both these early samples and throughout the storms is shown in Table 8.4 by high percentages 80 to 100% of well-developed silica features (Fuzzy score 3-4). The results through the storm are illustrated in Figure 8.4. A fairly high proportion of fresh sediment is entrained in the initial high intensity rainfall and transported in the discharge, as shown by Sample 2 in Table 8.4 and Figure 8.4. However, these particles are fine and slightly over-shadowed in Plates 68-73 by the aggregates left by the previous discharge. The pattern of discharge resembles that of Group I storms for approximately the first 2 hours. The high peak discharge (Sample 6) carries both fresh sediment and aggregates and largely clears the drain of the aggregates deposited by the last storm. As a result surface sediment features of

TABLE 8.4.
TABLE 8, 4,

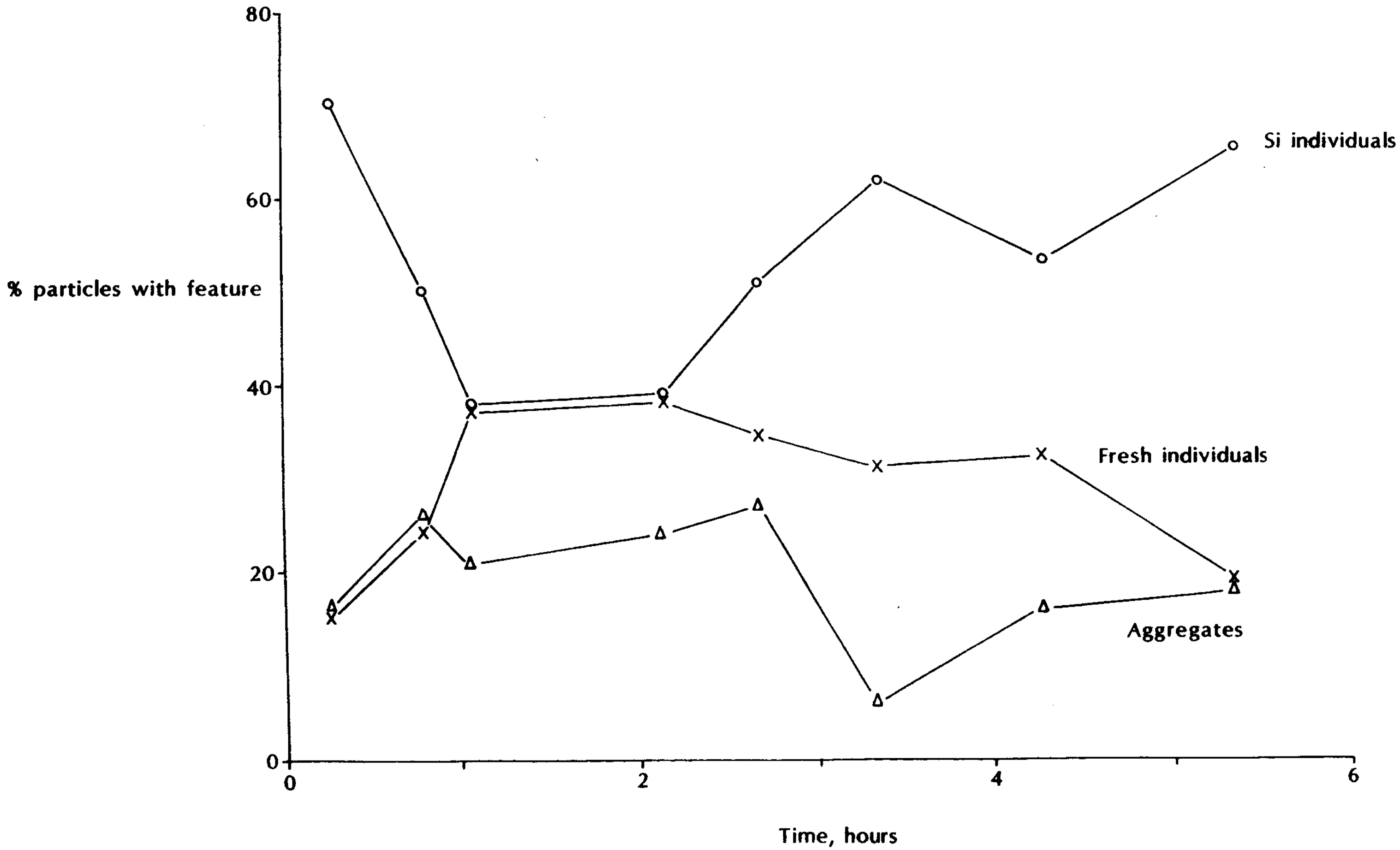
FUZZY ANALYSIS OF STORM SEDIMENT SAMPLES, 17.11.81.

Sample / Feature	2		6		8		16		20		25		32		40	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A @	2.4	35	4.9	24	5.0	21	3.1	38	3.5	20	2.8	21	3.2	19	5.0	7
B	3.9	90**	3.8	91**	3.5	79*	3.2	86**	2.9	100**	3.3	84**	3.0	91**	2.7	96**
C	2.1	55	2.9	59	2.0	20	2.4	33	3.1	42	2.3	21	1.5	19	2.3	23
D	2.6	80**	3.2	53	3.6	36	3.1	86**	3.4	60	2.9	79*	2.9	72*	2.7	82**
E	3.9	70*	3.8	64	3.8	43	3.6	76*	3.0	67	3.3	68	3.6	78*	3.5	56
F	1.1	40	2.1	22	2.0	29	1.5	62	2.5	30	1.4	53	1.5	56	1.5	48
G	2.8	95**	2.2	33	2.6	50	2.8	87**	3.0	50	2.6	74*	2.6	91**	2.8	82**
H																
I					5.0	36	3.0	5					3.0	3	3.0	15
J			5.0	11	4.0	7	5.0	5	5.0	20	3.5	11	5.0	6		
K																
Diatoms																

μ = Mean Fuzzy value of feature from sample particles
% = Percentage of particles with feature
71* = Notable values, 70-79
100**= High values, 80-100
@ = Feature list given in Table 7.3.

FIGURE 8.4.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 17.11.81.



STORM 17.11.81. OF MIXED GROUPING I/II.

Early Sediment of Small Aggregates and Coated Individual Particles Deposited by Previous Storm.

Plate 68 x 2500 Overall view; previously deposited aggregates and silica-coated individual particles; fresh particles (lower left).

Plate 69 x 4100 Advanced precipitation (left); eroded particles incorporated into aggregate (r.h.s.); organic material attached on right.

Plate 70 x 6000 Clear examples of advanced silica coating on subangular individual particles.

Plate 71 x 5800 Globular silica precipitation (a) and edge development of silica (b) on individual particles.

Plate 72 x 9000 Advanced silica precipitation-solution surface on subrounded individual particle.

Plate 73 x 5900 Edge development of silica on aggregate but fresh-face still untouched (a) and fresh material introduced (b).

Sample 6: Collected to Establish the Nature of Sediment Transported at Peak Discharge from Group I Rainfall.

Plate 74 x 2600 Well-developed large aggregate from drain at end of last storm.

Plate 75 x 5500 Detail of Plate 74; silica precipitation surface attacked by solution and probably abrasion; impact pits from collisions although at a reduced rate on falling discharge.


32μm
19.5
14μm
7.5μm
a
b
9μm
13.5μ
a
b
34μm
16μm

angularity and fresh faces are more clearly seen later in Samples 6 to 16 (Plates 74-90). However, surface sediment does not actually enter the drain in bulk until after further rainfall and approximately 3 hours of discharge flow. The resurgence of fresh sediment is shown by the dominance of fresh features in Sample 16 (Table 8.4, Figure 8.4, Plates 85-90). Spherical particles occur, signifying recent input and rapid transport to the outfall, but even so silica precipitation has had time to develop in this example (Plate 88).

It is interesting to note that Sample 8 not only contained the expected range of fresh sediment and silica feature remnants (Plates 81-84) but also distinctive material resembling clay particles (plates 77-80) which occurred in large conglomerations. No definite reason for their presence can be found but it is postulated that somewhere the rainfall entrained an isolated clay deposit which was able to reach the outfall relatively unscathed. Clay particles normally appear only rarely and, it is indicated, are easily eroded in stormwater transport (Chapter 7). In this case, it must have been weathered and transported through the system recently; its progress will have been made easier by the removal immediately before of the coarser, more abrasive sediment.

The exact nature of surface sediment and such occurrences as the unusual sediment input of Sample 8 in this storm raises some queries, which are equally applicable to all storms, on the scouring of the surface by rainfall. From the observations made in this study it is suggested that the surface sediment that is most readily available for entrainment in runoff is that lying freshly on the surface and subject to continual movement and abrasion by wind, water and traffic. After this material has been washed into the drain more sediment, which had previously lain lodged in crevices in the road surface and protected by the overlying sediment, is exposed

Sediment Dominated by Clay Particles.

Plate 76 x 5400 Detail of aggregate precipitation surface incorporating fine individual particles (→)

Plate 77 x 1300 Fragile clay-type sediment or possibly feldspar indicating low velocity transport and lack of vigorous abrasion.

Plate 78 x 5000 Detail of particles showing abrasion of fine layers which are possibly chemical splitting up of feldspar or authigenic clays; slight folding probably a feature of parent material.

Plate 79 x 3400 Detail of particle surface; particles appear slightly more massive than above (Plate 77,78) with conchoidal fracture and straight and conchoidal steps; faces are largely fresh and particles angular in outline; surface silica is developing both on plain faces and irregular edges.

Plate 80 x 3400 Small broken fragments (lower right) with irregular abraded edges and surfaces altered by abrasion and silica precipitation; more massive sediment (top right) with impact pits and conchoidal fracture.

Plate 81 x 8800 Well-developed silica precipitation on aggregate and incorporating fine individual particles; the aggregate is so well-developed as to be a remnant of the previous storm, still in the present discharge after over one hour.

Plate 82 x 5800 Silica precipitation on subangular subrounded particle; only moderately well-developed but with some degree of crystal formation indicating uninterrupted growth in low velocity flow, probably from late in previous discharge.

Plate 83 x 11900 Globular silica growth on sprawling aggregate.

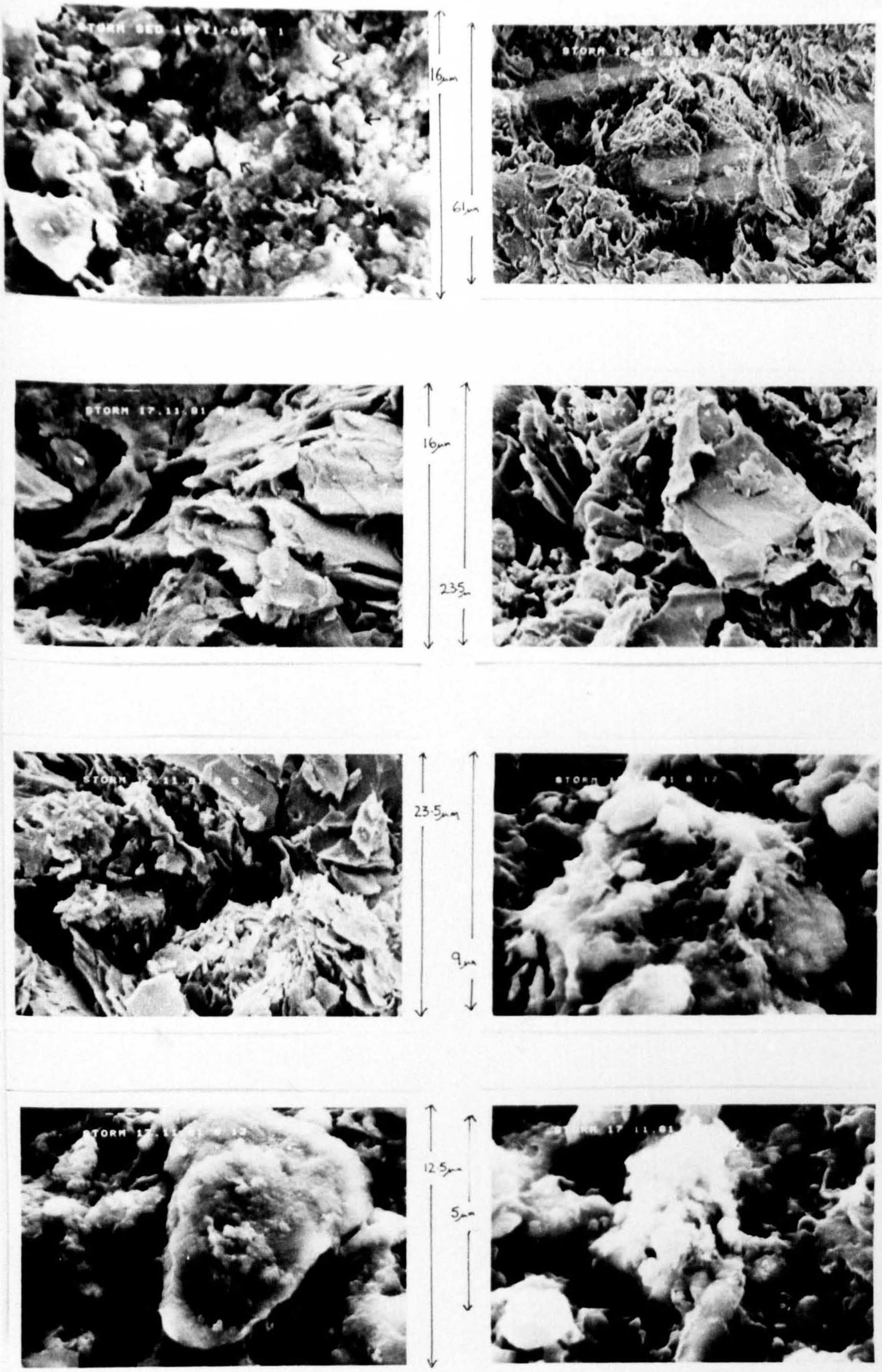

STORM 17.11.81
16µm
61µm
16µm
23.5µm
23.5µm
9µm
12.5µm
5µm

Plate 84 x 11900 Fresher sediment with rounded faces and pitting and abrasion features; adhering particles and silica precipitates (→).

Early Fresh Surface Material.

Plate 85 x 12300 Fresh surface sediment (2hours into storm); abraded, conchoidal steps; globular silica (a), adhering particles (→); a few remaining old aggregates.

Plate 86 x 16000 Fresh-faced angular particle with abrasion step features (right) and thin silica coat on angular particle (left)

Plate 87 x 5900 Diatom amongst fine, fresh-faced, angular particles which confirms the influx of fresh surface sediment but particles with advanced silica growth (lower right) still remaining.

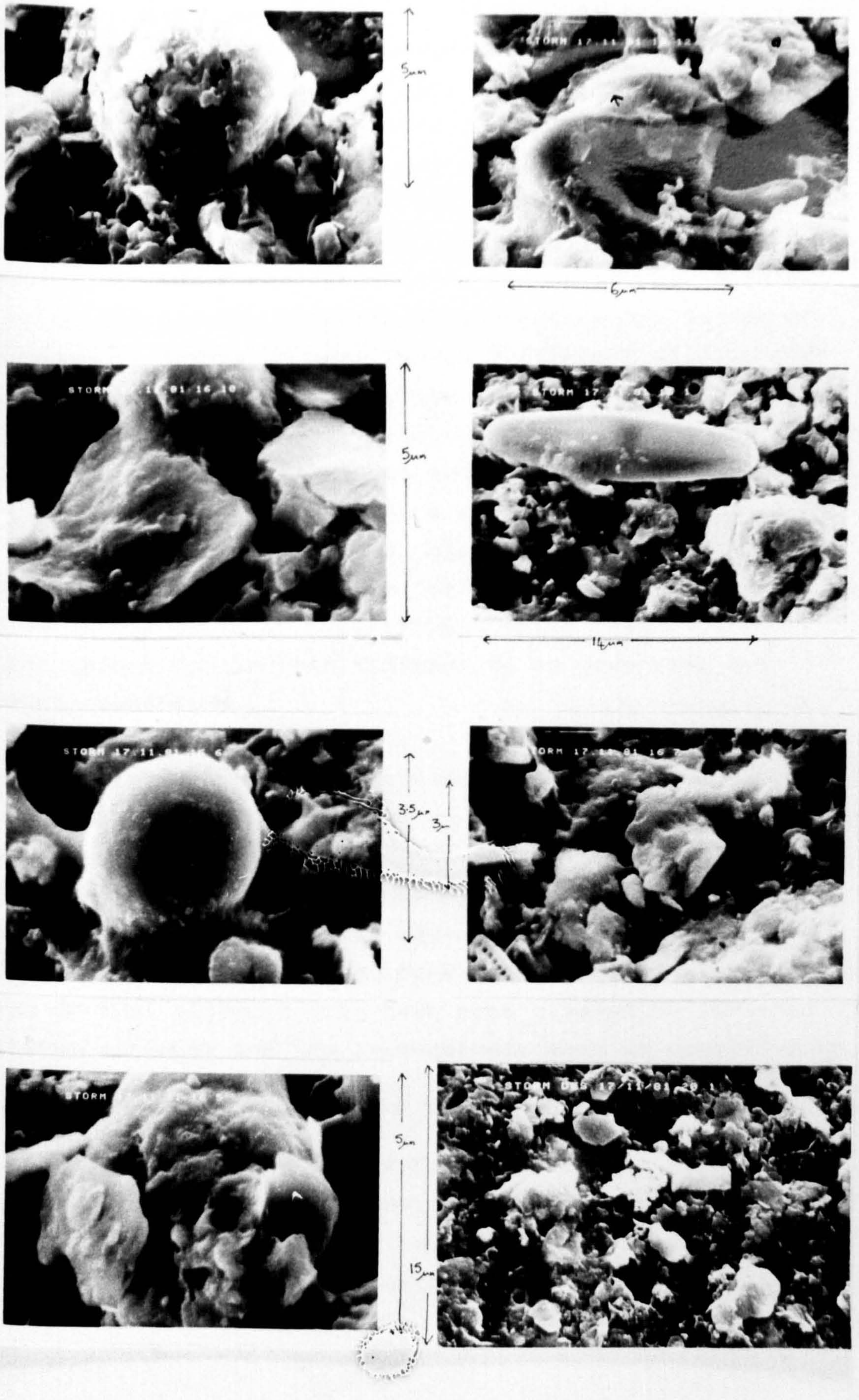
Plate 88 x 16000 Presence of spherical particle confirms recent input of material and slow transport; slow flow also demonstrated by silica precipitation possibly initiated in the gutter.

Plate 89 x 12200 Precipitation and abrasion features; precipitates in impact hollows where jagged surface may encourage precipitation; diatom fragment confirms slow flow which also aids precipitation growth.

Plate 90 x 16000 Fresh fragments becoming incorporated into an aggregate.

Renewed Sediment Input In Response to Prolonged High Intensity Rainfall Which Creates Substantial Discharge Peak.

Plate 91 x 6000 Overall view of small aggregates and relatively fresh individual particles, some with precipitation.


5μm
6μm
5μm
14μm
3.5μm
3μm
5μm
15μm

to runoff (Gutt and Nixon, 1972: as mentioned in Chapter 7). The material in the crevices is a little less heavily weathered and eroded than the overlying sediment and exhibits distinct impact features. It is washed into the drains only when the overlying material has been removed. The time scale involved in clearing the first sediment and then reaching the rather less accessible material is not clear. In storms of Groups I and II Fuzzy scores distinguish better-developed fresh features after the first few samples of the storm. This can be seen by the overall increase in percentage and degree of development in Sample 16 over Sample 2 (Table 8.4). However, as will be seen below, the very low intensity storms of Group IV remove only the most freshly available surface sediment (Table 8.6.). In the storm of 17.11.81 any surface sediment will only have been available for 11.5 hours as it has been shown above that the surface was fairly well cleared of sediment by the preceding storm. The change in fresh features between Samples 2 and 16 in the storm of 17.11.81 indicates that 11.5 hours was long enough for surface sediment to be generated and noticeably weathered.

Sample 20 (Plates 91-96) demonstrates the alteration of the sediment input at Sample 16 with an increase in the percentage of individual particles with silica features (Sample 16: 86%, Sample 20: 100%, Figure 8.4.) which have begun to be clustered together and are forming small aggregates. From Sample 25 onwards a slight but definite increase in fresh features occurs (Plates 97-103) although they have been altered by abrasion and silica activity and are increasingly seen as constituents of small aggregates. The renewed influx of surface sediment appears to be in response to the high intensity rainfall between the second and fourth hours of the storm and aggregate development was delayed until the rainfall abated which was not until Sample 28 of the discharge (Figure 8.6.). There is

Plate 92 x 12100 L.h.s. two relatively fresh particles altered by abrasion with impact pits (right) and conchoidal fracture with steps (a); r.h.s. two particles altered substantially by surface silica precipitation and solution and appear to be cemented together by precipitate (b).

Plate 93 x 8900 Relatively fresh-faced, angular, abraded particles with edge steps; early precipitation (right) and cementing the two particles together.

Plate 94 x 12000 Fresh-faced rounded particles with silica precipitation and adhering particles.

Plate 95 x 16000 R.h.s. very fresh-faced angular particle with horizontal cleavage planes creating stepped edges; l.h.s. rounded particle with dense silica precipitation and solution features.

Altered Sediment From Renewed Surface Input.

Plate 96 x 5900 Aggregate of varied particles with little silica spread indicating a newly forming aggregate of relatively fresh sediment.

Plate 97 x 12000 Fresh-faced particle (a) in contrast to heavily precipitate-covered particle (b).

Plate 98 x 12300 Mainly relatively fresh sediment, angularity and fresh faces seen beneath early precipitation and some edge abrasion.

Plate 99 x 16000 Detail of recently input particle (confirmed by diatom fragment) showing multiple fresh faces and edge abrasion (⇒).

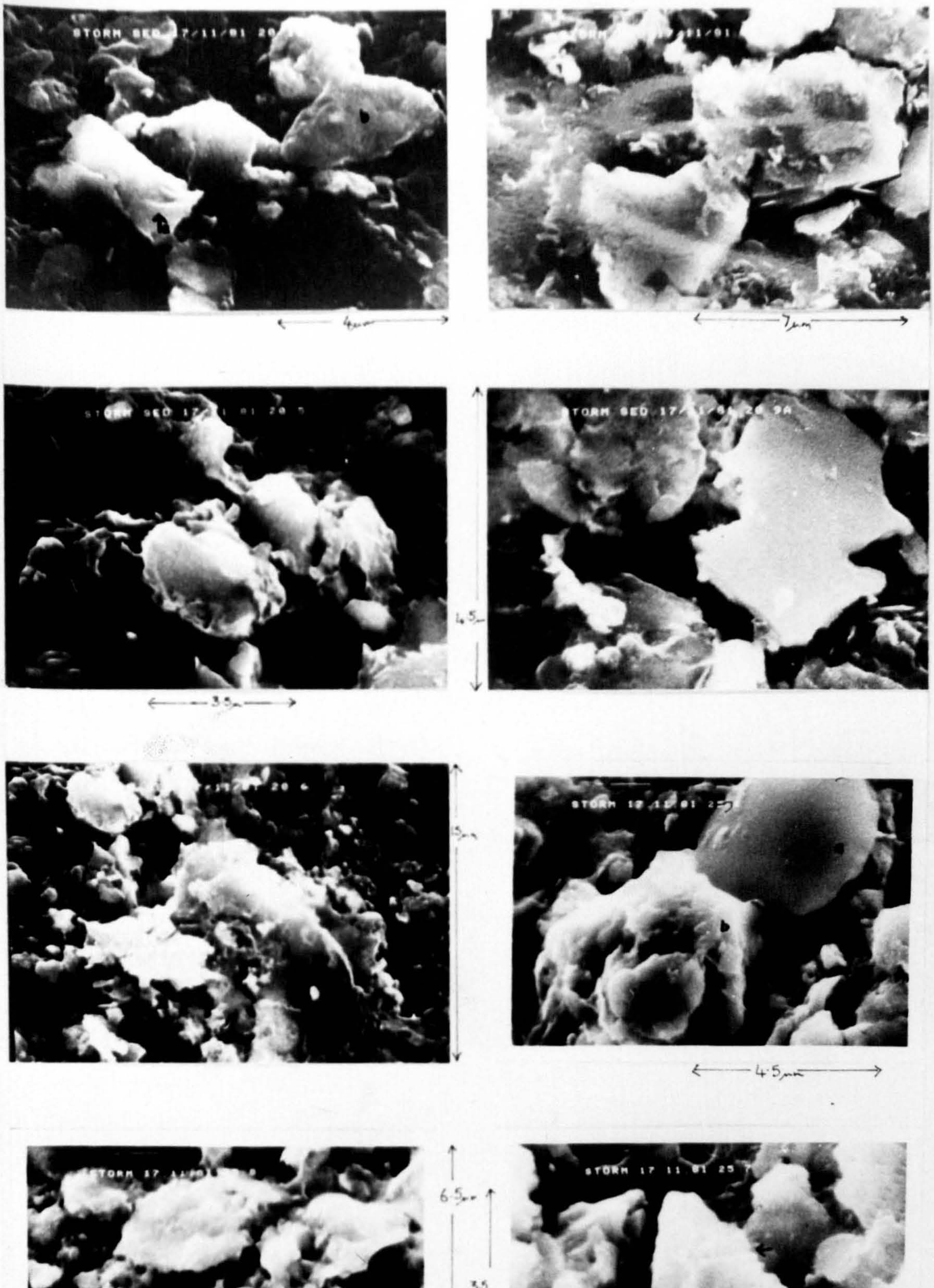

STORM SED 17/11/81 20
4μm
7μm
3.5μm
4.5μm
5μm
4.5μm
6.5μm
3.5μm

Plate 100 x 16000 Detail of recently input sediment with fresh faces (a) and edge erosion (b)

Plate 101 x 9300 Fresh and altered sediment: r.h.s. fresh-faced particle with abraded edges (a) and low relief impact pits adhering fragment (centre face); r.h.s. substantial precipitation on aggregate incorporating fresh angular fragments (b).

Plate 102 x 6000 Early aggregate development of cemented, slightly altered individual particles and some well-developed silica growth indicating slow flow; no longer any sign of old aggregates from previous storm.

Plate 103 x 12400 Very early stage of sediment clustering and cementing into aggregate; constituent particles are angular individuals of fresh faces.

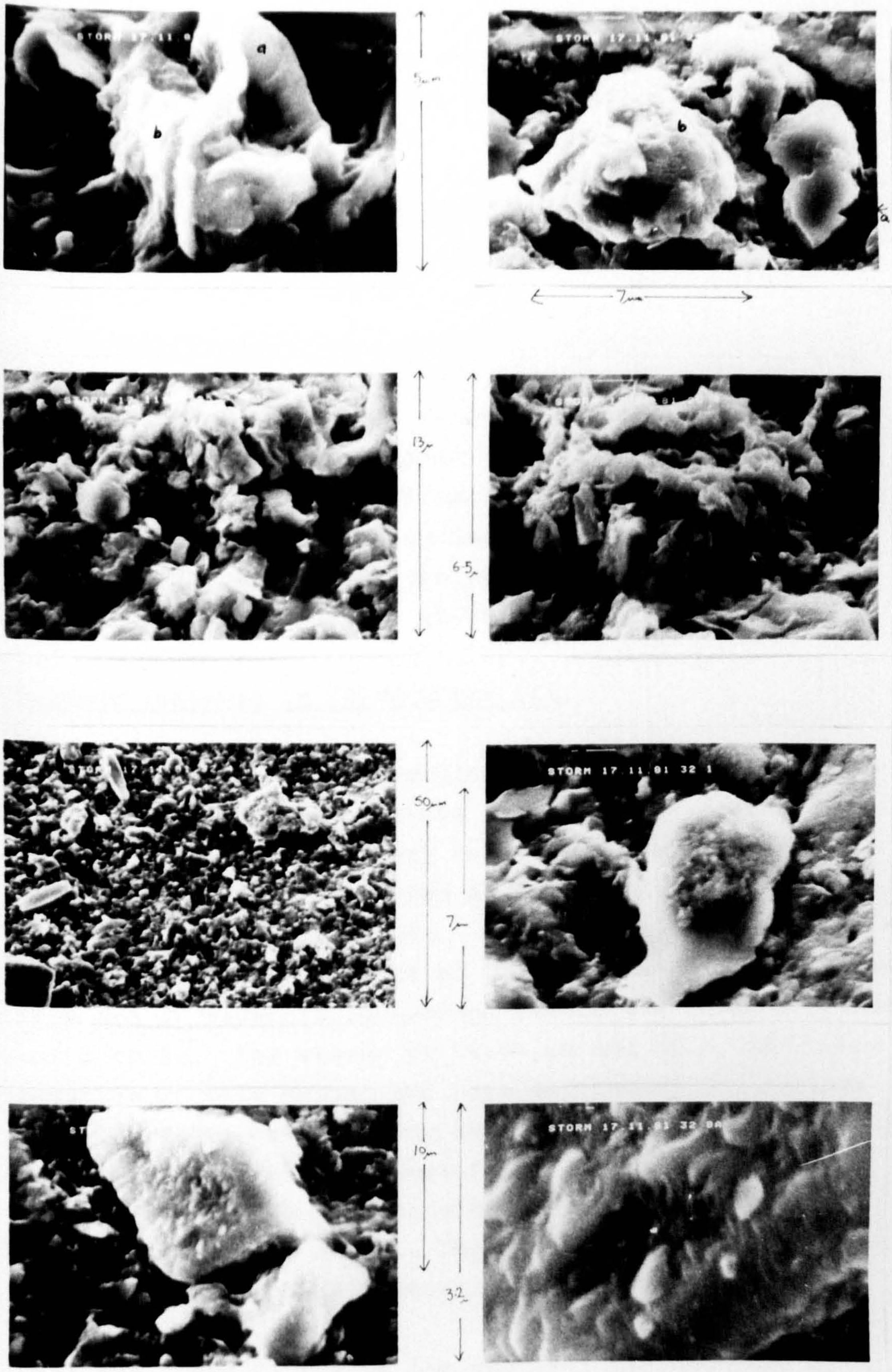
Aggregate Formation.

Plate 104 x 1600 Overall view of wide range of sediment from fresh-faced angular particles and diatoms indicating continuous small scale surface input, to altered individual particles and aggregates.

Plate 105 x 9000 Silica precipitation with solution across fresh-face of sub-angular particle with abraded adges.

Plate 106 x 5200 Subangular particle with precipitation solution surface.

Plate 107 x 25000 Detail of Plate 106; precipitation growth and fine adhering fragments; solution hollows in precipitation and particle surface.


a
b
5μm
b
7μm
13μ
6·5μ
50μm
STORM 17 11 81 32 1
7μ
10μm
3·2μ
STORM 17 11 81 32 9A

an increasing trend in silica activity towards the end of the storm discharge, as can be seen from Sample 32 (Plates 104-111) and Sample 40 (Plates 112-121) on Figure 8.4. The percentage of fresh material decreases as the aggregates and individual particles with silica precipitates increase. Although sampling ended at this point the discharge has a little way to fall to regain the base flow. During these low discharges (1.5-2.5 m^3/s) and the subsequent drying of the drain aggregate development was expected to continue.

The example of the storm of 17.11.81 serves very well to confirm the features attributed to the sediment transported in both its constituent storm types. It is a rare exception to the four group storm classification but its hydrological characteristics are clearly recognised as a combination of those from Groups I and II and the resulting sediment characteristics are in response to them.

8.5. Surface Textures in Storm Group III.

Recalling the hydrological classification in Chapter 3 it will be seen that in the storms of Group III discharge gradually increases with rainfall intensity to reach a peak of between 2.75 and 4.50 m^3/s over a period of 1.25 to 1.75 hours and decreases again at a similar rate. The pattern of rainfall and discharge is similar to that of Group II storms but all the parameters are of moderate dimensions within the range provided by Groups I to IV. The storms of 14.11.80 and 10.9.81 (Figure 3.4) are representative of this group and have antecedent dry periods of 179 and 505 hours respectively during which time substantial surface sediment will have accumulated. The storm preceding 14.11.80 was of Group II and therefore it is likely that some material was left in the drain. The storm 14.11.80 is used as the main example of Group III storm.

Throughout the storm discharge the sediment is dominated by aggregates and silica-altered individual particles. The

Plate 108 x 8300 Small aggregate in early stage of development with pronounced silica growth (a) incorporating relatively fresh particles (b).

Plate 109 x 11700 Small aggregate, particles fairly spread out with interparticle cement (a) and limited surface growth (b) leaving fresh or abraded particles still exposed elsewhere (c).

Plate 110 x 11000 Further aggregate development forming a larger aggregate than Plates 108 or 109; silica cement (a) incorporating fresh sediment (b) and developing an upper surface (c).

Plate 111 x 5000 One or more particles exhibiting widespread silica precipitation (a) although angularity and freshness of face of exposed particles indicates immature formation (b).

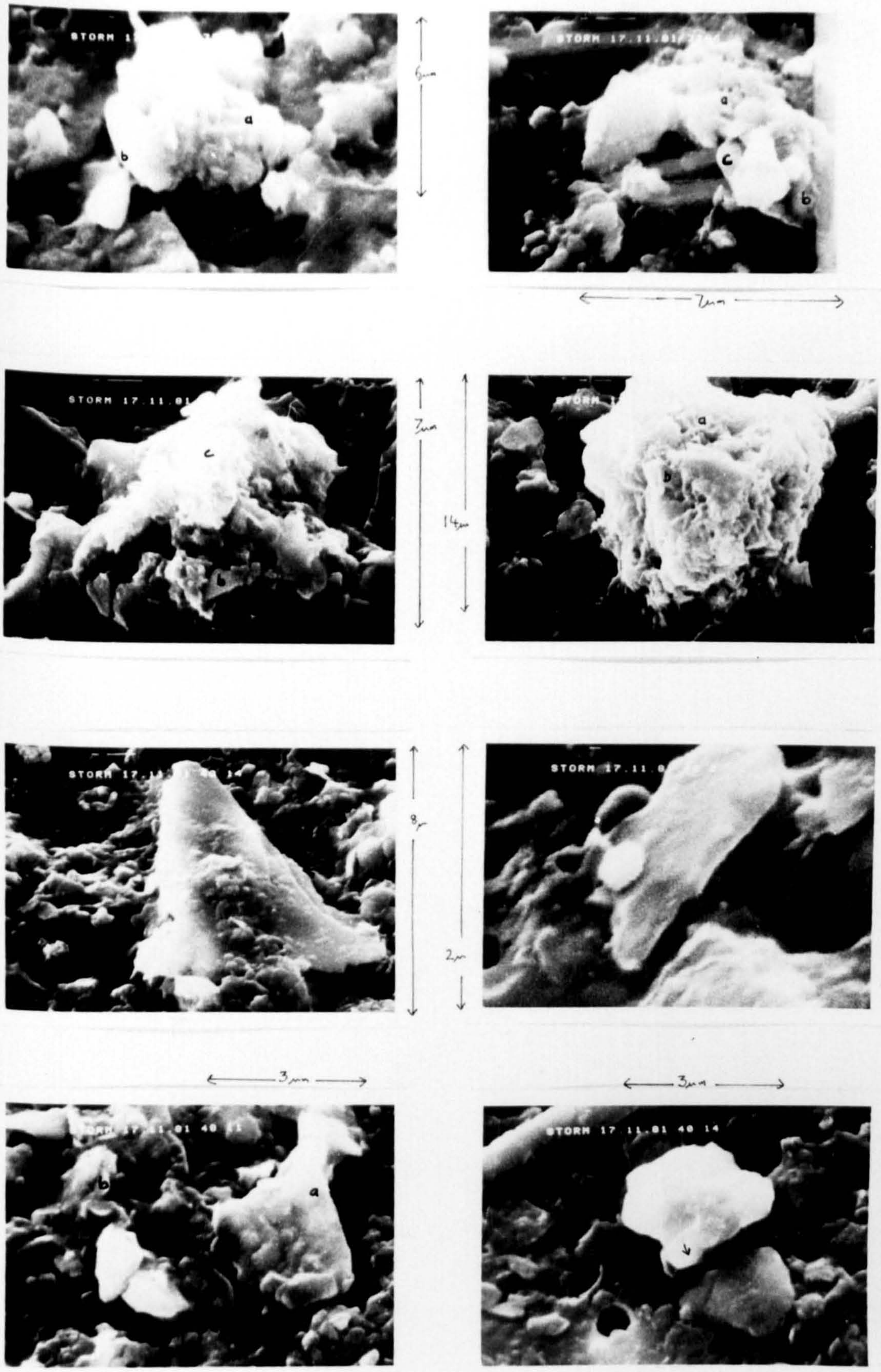
Advancing Precipitation and Aggregation.

Plate 112 x 9000 Angular particle with impact and step feature (→) and precipitation and solution surface.

Plate 113 x 37000 Detail of subangular fine particle showing abraded edges and irregular precipitation solution faces.

Plate 114 x 15000 More advanced silica precipitation (a) on subangular material (eg. r.h.s.) and clustering (b) and cementation of particles.

Plate 115 x 15000 Silica precipitation on surface of angular fresh-faced particle with step abrasion (→) features (upper particle, charging) and surrounding weathered material with precipitates.



STORM 17.11.81
6µm
a
b
7µm
c
14µm
8µ
2µm
3µm
3µm
STORM 17 11.81 40 14

Plate 116 x 15000 Advanced silica growth over particles (charging).

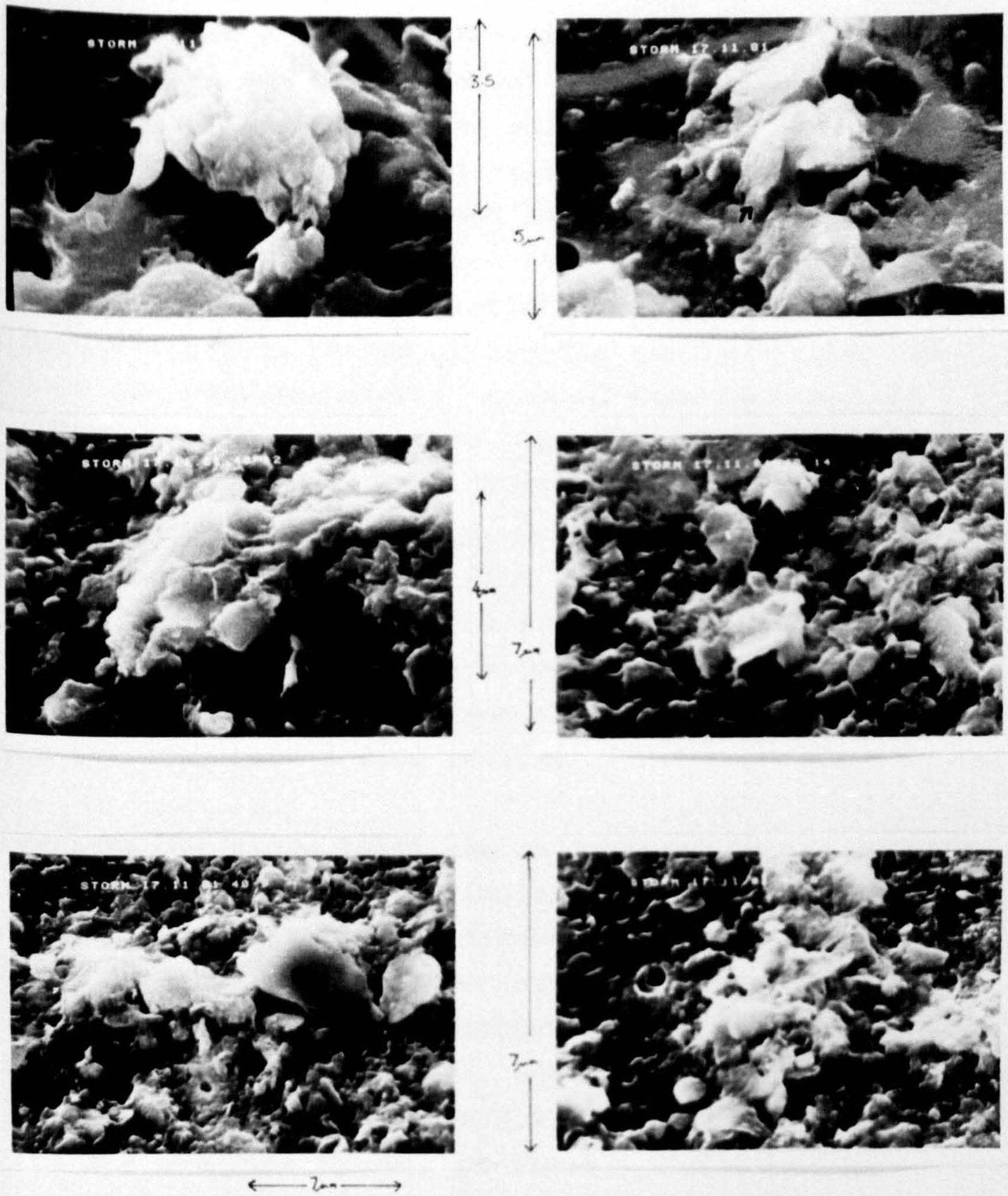
Plate 117 x 15000 Clustered fresh abraded particles with impact pits and adhering particles, possibly already held together by silica cementation (→).

Plate 118 x 11800 Developing aggregate with particles of mixed stages of alteration; widespread silica precipitation.

Plate 119 x 11500 Widespread silica precipitation cementing together adjacent individual particles.

Plate 120 x 5700 Small aggregate (left) in contrast to fresh-faced angular particle, right, and surrounding altered fine individual particles (→).

Plate 121 x 115000 Aggregate developing from visible fine constituent particles and coated and cemented by silica precipitation.


STORM 17.11.81
3.5
5μm
4μm
7μm
7μm
7μm

occurrence of aggregates follows a similar, although slightly modified, pattern to that of Group II storm loads. In the early low discharge (Plates 122-124) the sediment concentration is low and comprises mostly individual particles severely altered by silica precipitation and solution (Fuzzy score 3.8, 75% coverage, Table 8.5). Aggregates are well-developed (Fuzzy score 4.0, Table 8.5) and too large for the capacity of the discharge at this stage. The well-developed silica features of both individual particles and aggregates points to their having been formed during the slowly falling discharge of the previous storm. Some surface sediment is introduced at this time but the moderate Fuzzy values of the features of fresh face (2.5) and angularity (3) suggest a prior period in moisture allowing silica precipitation. The higher value (3.7) for impact pits indicates the long period of erosion during the antecedent dry period. Indeed, surface sediment input throughout this storm (Table 8.5, Figure 8.5) was weathered and eroded and thus confirmed the effects of surface activity over a long period.

An hour into the storm there was an increase in the quantity of sediment of all types, particularly of the aggregates, now easily transported by the discharge, and of surface sediment entrained by the higher rainfall intensity (Plates 125-129). The well-developed nature of the aggregates (Fuzzy score 4, 80%, Table 8.5) and individual particles with precipitation (Fuzzy score 3.8, 100%) showed their origin to be in the previous storm. Conversely, the poor Fuzzy scores for the fresh features (2 to 2.8) indicated the alteration of surface material.

The old aggregates are removed during the second hour of the discharge and by Sample 16 (Plates 130-134) small new aggregates are forming from the surface material. Much of the already-weathered surface material develops silica precipitates rapidly during the moderate discharge and these particles readily form cemented aggregates. There is a slight increase

TABLE 8.5.

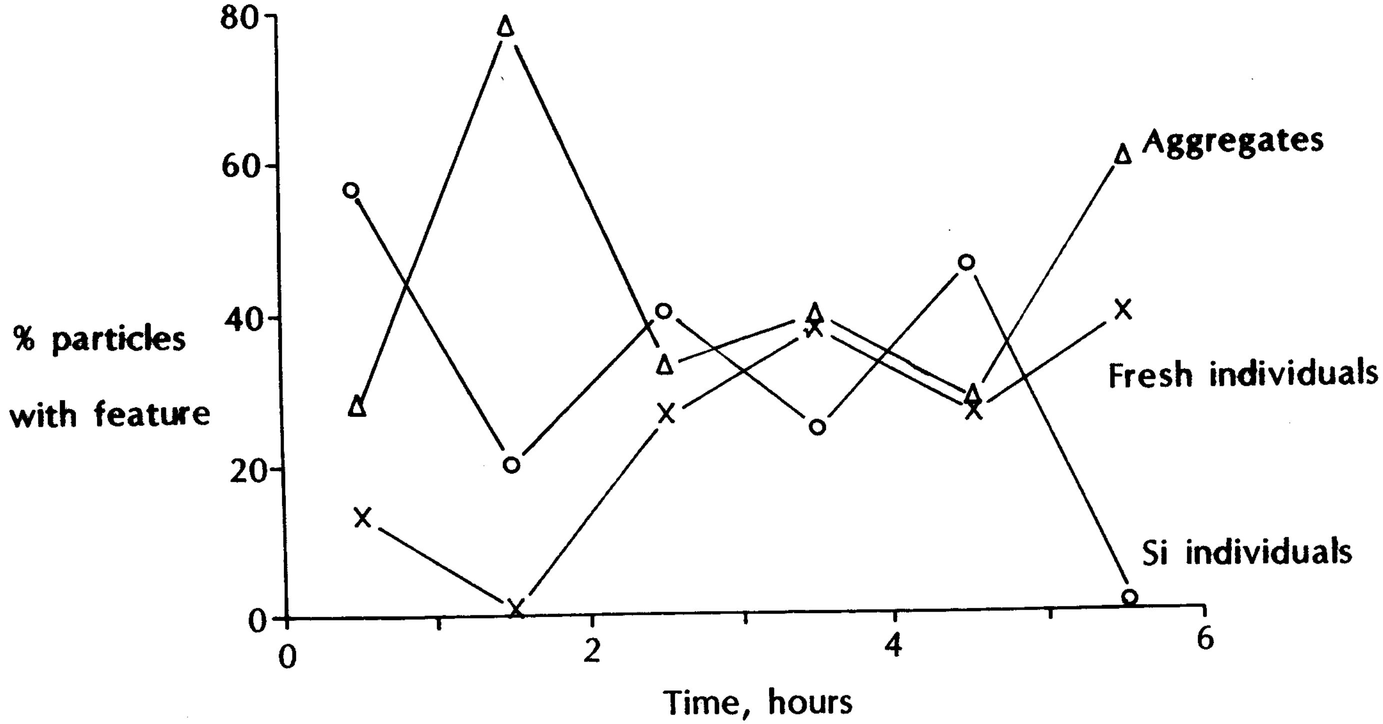
FUZZY ANALYSIS OF STORM SEDIMENT SAMPLES, 14.11.80.

Sample Feature	3		8		16		26		32		46	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A@	4.0	25	4.0	80**	4.2	23	4.3	38	4.7	27	5.0	60
B	3.8	75*	3.6	100**	3.8	100**	3.1	100**	3.7	91**	3.3	80**
C	3.8	63	2.4	100**	2.8	69	3.1	88**	2.8	55		
D	2.5	50	2.2	100**	2.8	62	2.9	88	2.4	91**	3.5	80**
E	3.0	38	2.4	100**	3.1	69	3.3	88	3.0	64	3.8	80**
F	3.0	38	2.0	20	2.3	23	2.3	50	1.6	46	2.0	40
G	3.7	38	2.8	100**	3.5	46	3.5	75	2.8	36	2.8	80**
H	1.0	13										
I											5.0	40
J			1.0	20								

μ = Mean Fuzzy value of feature from sample particle.
% = Percentage of particles with feature.
71* = Notable values, 70-79.
100**= High values, 80-100.
@ = Feature list given in Table 7.3.

FIGURE 8.5.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 14.11.80.



STORM GROUP III

Mixed Sediment Types From the Early Stages of Group III Storm: 14.11.81.

Plate 122 x 2500 Mature, well-developed aggregate deposited by previous storm, low overall sediment concentration in response to low flow.

Plate 124 x 5500 Individual particles with substantial silica features developed during previous storm; lower; recently input surface sediment, feldspar (cleavage) surviving thus far; surface impact or solution pits.

Plate 126 x 5600 Increasing discharge, after 1 hours storm flow, is still clearing the drain of previously deposited aggregates (above) with well-developed surface precipitation and solution features and adhering particles.

Plate 123 x 5600 Severely altered individual particles by abrasion (upper) and solution pitting (→) in abraded hollows indicating a period of slow flow after abrasion in previous storm lower: abrasion, silica precipitation and solution.

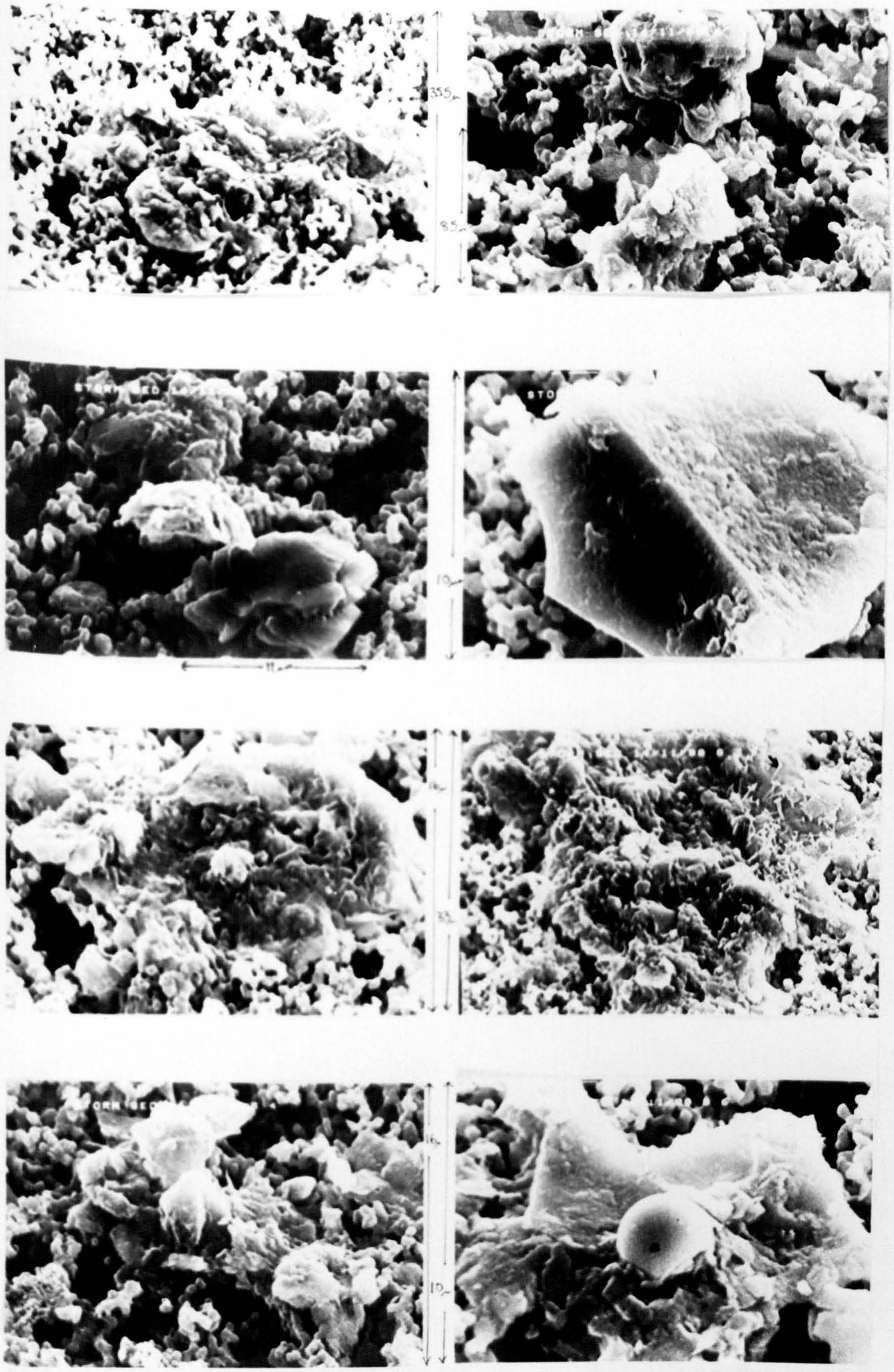
Increasing Quantities of Sediment.

Plate 125 x 8600 Increasing discharge transports a greater load but largely of old aggregates and surface individual particles (above). Angular particle with conchoidal edge fracture, surface cracks and early silica precipitation.

Plate 127 x 2700 Advanced aggregate development with possible biological material (→).

Plate 128 x 5700 Small aggregate of old silica-coated material and incorporating more recent surface sediment.

Plate 129 x 8800 Abraded angular particle with both fresh faces, aggregated particles and silica precipitation; abraded spherical particle with minor precipitation (a); probably recently input from surface, gutter flow and slow drain flow combining to allow alteration.



New Aggregate Formation.

Plate 130 x 2600 Recent aggregate with minimal surface silica coating but incorporating well-developed silica altered individuals (a) and fresh angular surface sediment (b).

Plate 131 x 8600 Abraded angular particle or cluster with early precipitation on fresh-faces probably the result of surface weathering during long accumulation period; fine "granular" silica could have formed during slow gutter and drain flow since this storm began 2 hours previously.

Plate 132 x 5700 Well-altered individual particles, first by abrasion, later by precipitation during 179 hour accumulation period. This is surface sediment most recently input and explains such altered individuals occuring after aggregates of the previous storm.

Plate 133 x 5700 Rounded particle of globular silica precipitation-solution surface attached to aggregate.

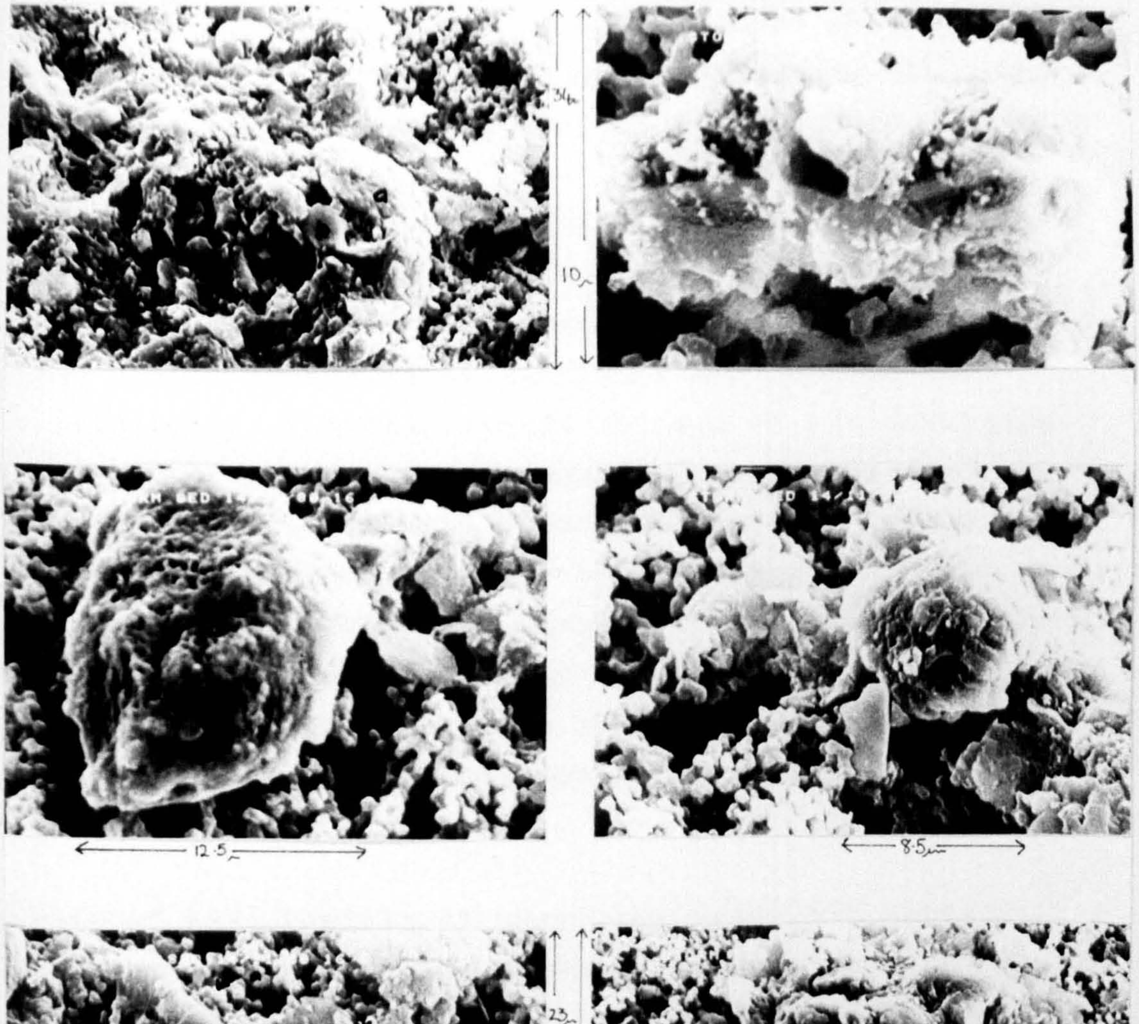
Increasing Aggregate Development.

Plate 134 x 3900 Clustered, altered individual particles with recent surface "granular" silica precipitation; millipore filter (→).

Plate 135 x 2500 Fast increasing aggregate development of recent surface individual particles.

Plate 136 x 2600 Recently formed aggregate of surface sediment.

Plate 137 x 11600 Severely abraded individual particle with impact pits (→) and irregular eroded edges and faces; a little early silica precipitation.


34µ
10µ
12.5µ
8.5µm
23µ
36µ
34µ
8µ

in the clarity of fresh features (Table 8.5) which can be explained by the particles having been covered on the surface by other sediment (Samples 3 and 8) which bore the brunt of erosive forces and was removed earlier in the storm.

The newly formed aggregates and their surface precipitates develop rapidly in the low discharge where precipitation appears to be more dominant than abrasion (Plates 135-139). Aggregate growth continues as particles are incorporated (Plates 140-145). Finally, towards the end of the discharge (Plates 146-148) after over six hours, the aggregates are extremely well-developed with a Fuzzy score of 5 (Table 8.5). They have increased progressively in development and occurence from 4.3, 38% to 5, 60% between Samples 26 and 46 respectively. Precipitation will continue for as long as flow permits. The final percentage of aggregates is however lower than that (80-100%) deposited by the long period of falling discharge of Group II storms.

A minority of fine, individual particles reach the outfall late in the storm and are the freshest material monitored during the storm. They are probably a combination of recently-eroded surface sediment and fragments abraded from drain load. Surface material remains a possibility at this late stage in the storm in response to a small revival in the rainfall intensity after 2 hours.

8.6. Surface Textures in Storm Group IV.

Storms in Group IV are those of shortest duration and generate the lowest rainfall totals and intensities. One such storm is that of 26.11.80 which produces only 1.1mm in 3.5 hours (Figure 3.5). It was preceded by a Group I storm with 169 dry hours between the two storms. There were two minor occurrences of rainfall during that period with the result that some fine sediment

Plate 138 x 15000 Complete low relief cover of silica precipitation-solution surface.

Plate 139 x 8700 Solution and silica precipitation on weakly structured particle (a); fresh-faced angular particle with edge precipitation (b).

Further Aggregate Development.

Plate 140 x 1400 Increased aggregate development with overall precipitation incorporating last of fresh input as demonstrated by battered diatom test (a) and pollen (b); flow reduced in falling discharge, 4 hours since onset of stormflow.

Plate 141 x 3800 Severe silica alteration on particles incorporated into aggregate

Plate 142 x 8800 Unbroken silica coating of subangular particle with adhering particles indicating slow flow and minimal abrasion.

Plate 143 x 8600 Further example of silica coating as in Plate 142, solution hollows shown upper left of particle.

Plate 144 x 8700 Extensive well-developed silica precipitation-solution (a), surface erosion and precipitation (b)

Plate 145 x 11800 Abrasion of fresh-faced angular particle with cracks (a), straight (b) and conchoidal steps, large and small scale impact pits (c), irregular edges and adhering fragments; unusual amongst such greatly silica altered material.

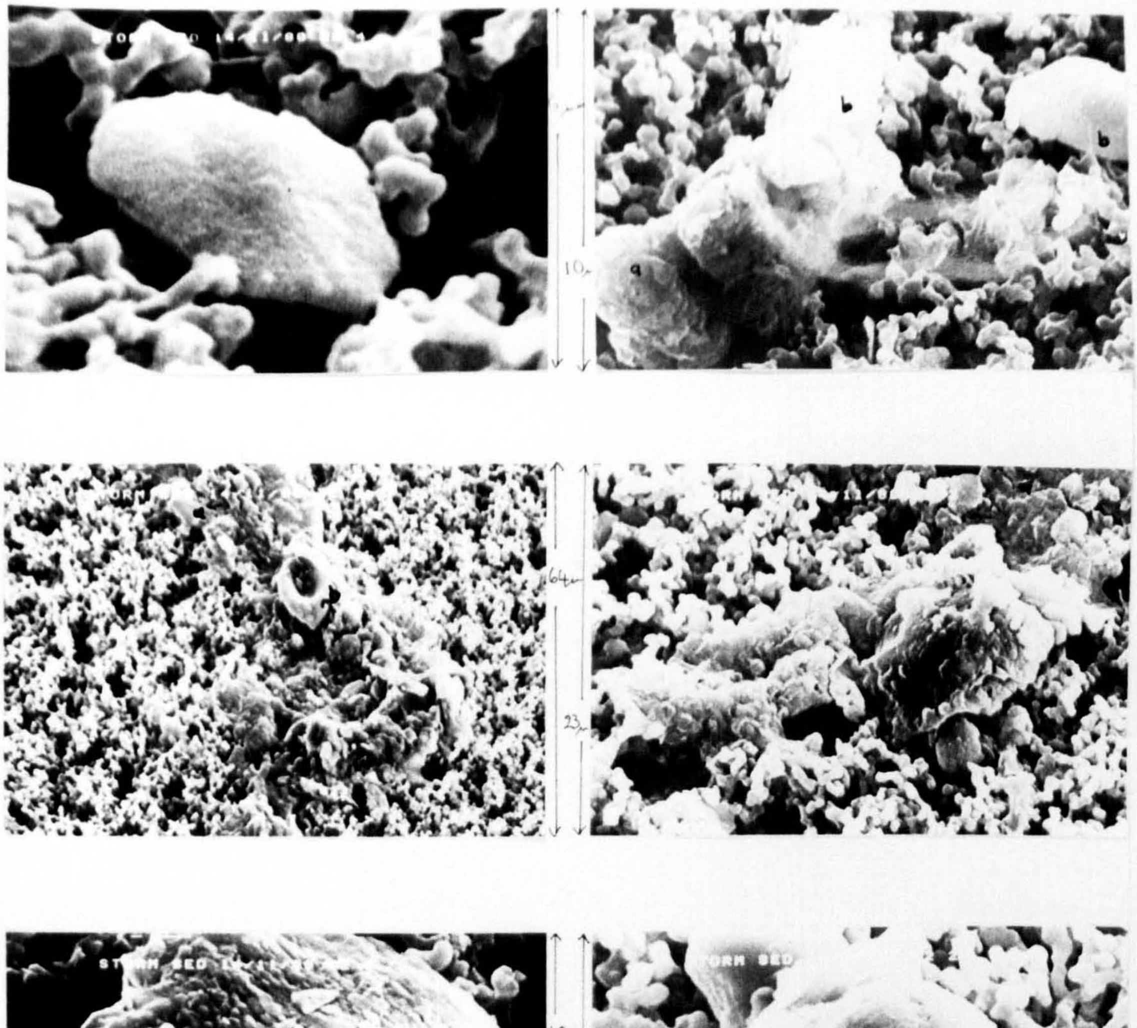

STORM SED
10μ
a
b
64μ
23μ
10μ
10μ
10μ
7.5μ

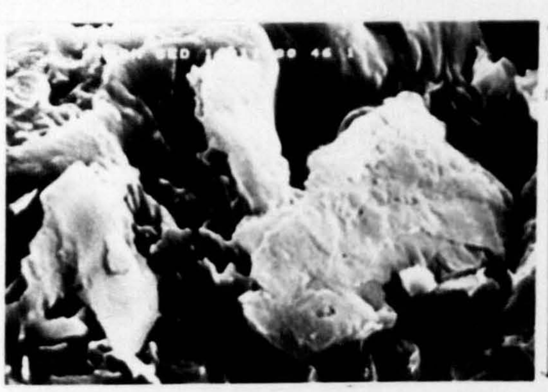
Plate 146 x 1500 Silica coating of aggregated material.

Plate 147 x 2600 Detail of silica coating and fine angular fragments from such particles as shown in Plate 145.

Plate 148 x 5400 Silica precipitation on fresh-face.


60µm


19µm


16.5µm

might be expected to have been deposited in the drain.

The low capacity of the discharge means that the sediment load is very small at all times during the storm. Fine individual particles with moderately well-developed silica precipitation form the majority of the load throughout the storm as is shown in Table 8.6, Figure 8.6. Fuzzy values of silica precipitation on individuals range from 3.3 to 4.0 in 70-100% of the particles. Early in the storm the fine, altered, individual particles will be largely the drain sediment of the previous storm which is initially transported in preference to the heavier aggregates. Later, altered individual particles will comprise surface sediment which has had a significant accumulation period for erosion; and intermittent showers which provide moisture for silica precipitation in the gutter (Plates 149-153). The precipitation of silica continues rapidly in the drain, encouraged by the conditions of slow flow, and aggregates are formed. The size of the aggregates is limited at this stage by the lack of sediment and by the low load capacity of the discharge.

As the storm progresses (Plates 154-158) there is an increase in the surface material with moderately well-developed impact breaks (Sample 8, Table 8.6) but textures are still dominated by silica features. After two hours into the storm aggregate formation is well under way (Plates 159-163). Rainfall intensity and discharge have risen and there is an increase in the quantity and freshness of surface sediment. Surface sediment is collected in small quantities compared with the other storm groups and comprises first the material most freely available which tends to be moderately well eroded, and, later, particles of slightly fresher appearance. The rainfall is of insufficient intensity to erode and entrain very much fresh source material and as a result the surface sediment collected will be that lying closest to the drain in the area of rainfall. Due to the low discharge the surface

TABLE 8.6.

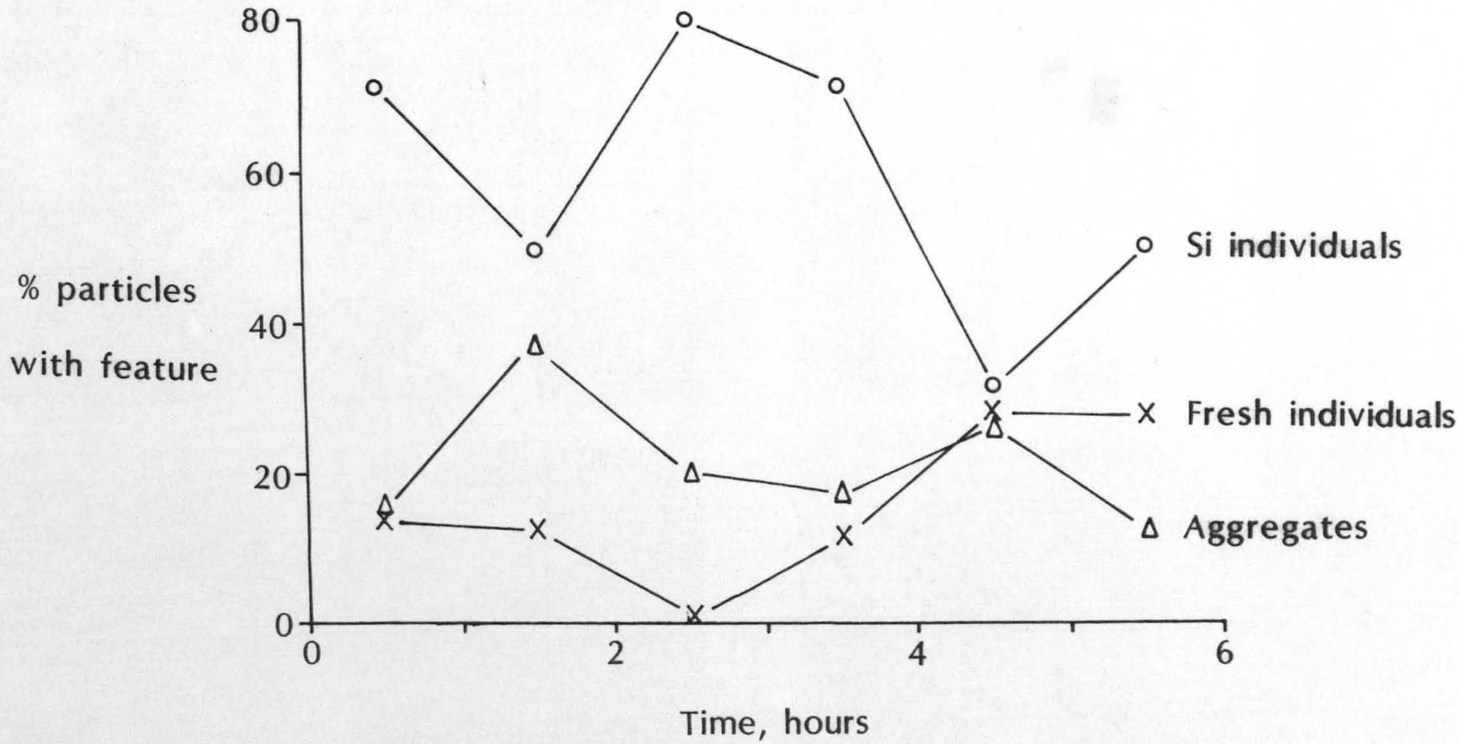
FUZZY ANALYSIS OF STORM SEDIMENT SAMPLES, 26.11.80.

Sample / Feature	4		8		16		25		34		46	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A@	3.2	30	4.7	38	2.5	50	4.3	17	4.8	30	5.0	12
B	4.0	90**	3.6	100**	3.5	100**	3.6	90**	3.8	70*	3.3	100**
C	2.8	50	2.3	38	2.8	100**	3.3	17	3.4	35		
D	2.7	45	3.5	25	2.0	50	3.0	60	3.2	70*	2.7	75*
E	3.0	55	2.8	63	2.5	50	3.5	67	3.2	70*	3.3	75*
F	2.0	5	2.0	13			2.5	11	3.3	23		
G	2.0	15	3.8	63	3.5	50	3.0	17	3.0	20		
H	1.0	20										
I							4.0	5				
J	1.0	5	1.0	13			1.0	11	1.0	7	1.0	12

μ = Mean Fuzzy value of feature from sample particle.
% = Percentage of particles with feature.
71* = Notable values, 70–79.
100** = High values, 80–100.
@ = Feature list given in Table 7.3.

FIGURE 8.6.

PERCENTAGE VARIATION OF AGGREGATES, SILICA-ALTERED AND FRESH INDIVIDUAL PARTICLES DURING THE STORM OF 26.11.81.



STORM GROUP IV.

Low Concentration Sediment of a Group IV Storm, 26.11.81: Early Storm, Slightly Altered, Individual Sediment and Small Aggregates.

Plate 149 x 11500 Abraded surface sediment; accumulation period of 169 hours is sufficient for considerable surface abrasion.

Plate 150 x 32000 Angular particle with abrasion and precipitation features therefore fresh surface sediment (after 0.5hr. flow) with period of slow flow transport.

Plate 152 x 16000 Particles with silica precipitation surfaces could be either recently introduced or remnants of previous flow, a Group I storm which would have only left a little sediment.

Plate 151 x 8700 Detail of Plate 152, top cluster: r.hs. small aggregate with weakly developed silica coating, probably left from last storm.

Fresh Sediment and Early Aggregation.

Plate 153 x 8700 Small aggregate deposited by previous storm with surrounding individual particles recently input from the surface.

Plate 154 x 2500 Overall view of fresh, slightly altered, surface material and small aggregates some from previous storm, many forming throughout low flow of this storm discharge.

Plate 155 x 14000 Detail of fresh, surface material slightly altered during relatively long accumulation period and silica growth during present flow.

Plate 156 x 15000 Fresh, angular, surface sediment with early silica precipitation.

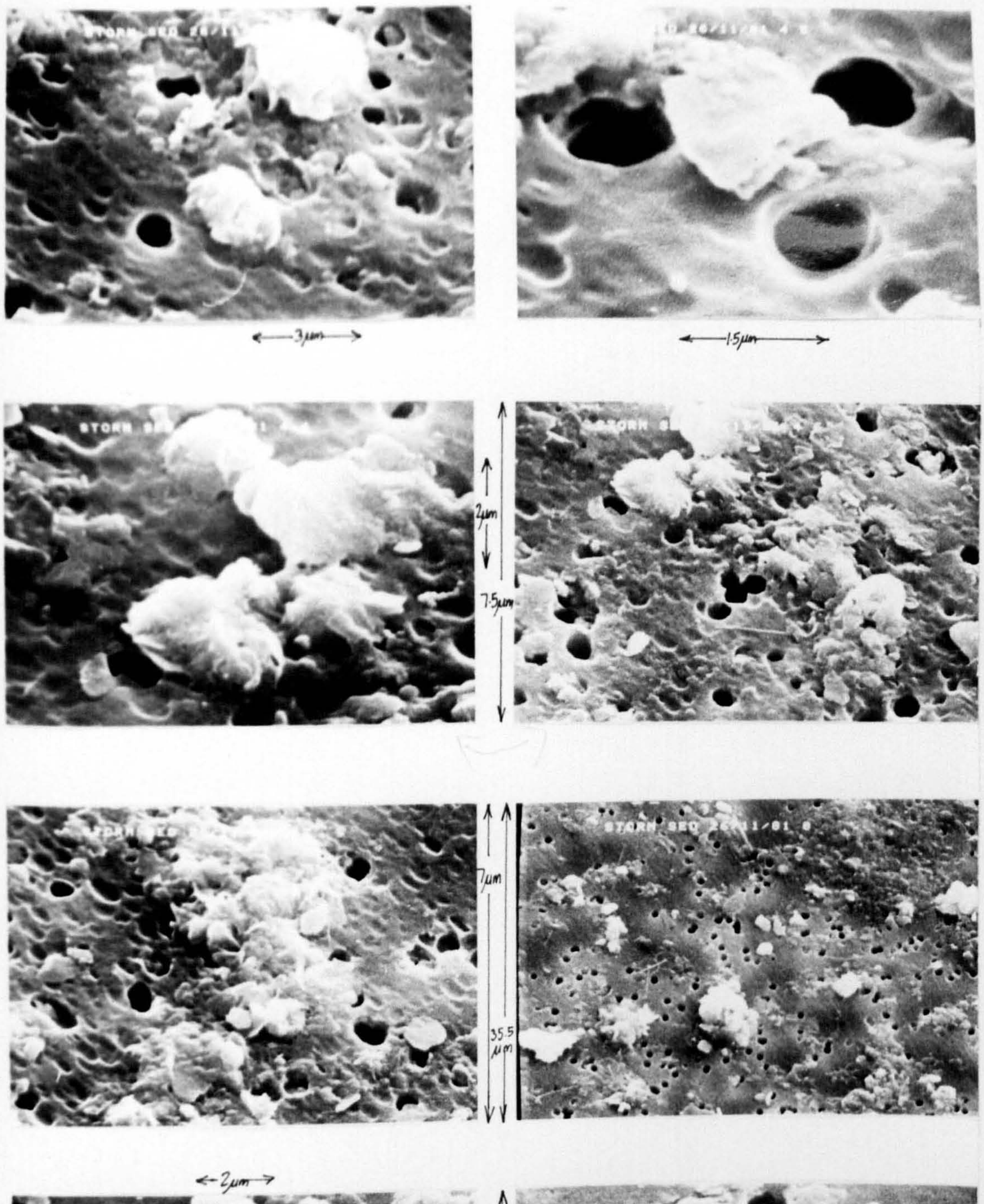

3μm
1.5μm
2μm
7.5μm
7μm
35.5 μm
2μm
6μm

Plate 157 x 15000 Small aggregate, possibly originating in previous storm due to advanced silica growth (lower centre) but incorporating recently input sediment (top).

Plate 158 x 11500 Similar situation to Plate 157, globular silica growth (a) fresher sediment at extremeties.

Increasing Silica Precipitation and Aggregation.

Plate 159 x 2700 Overall view showing increasing concentration of sediment after 2 hours flow, very little surface material entering drain by this time due to low intensity of rainfall.

Plate 160 x 15000 Increasing silica precipitation and solution features on individual particles.

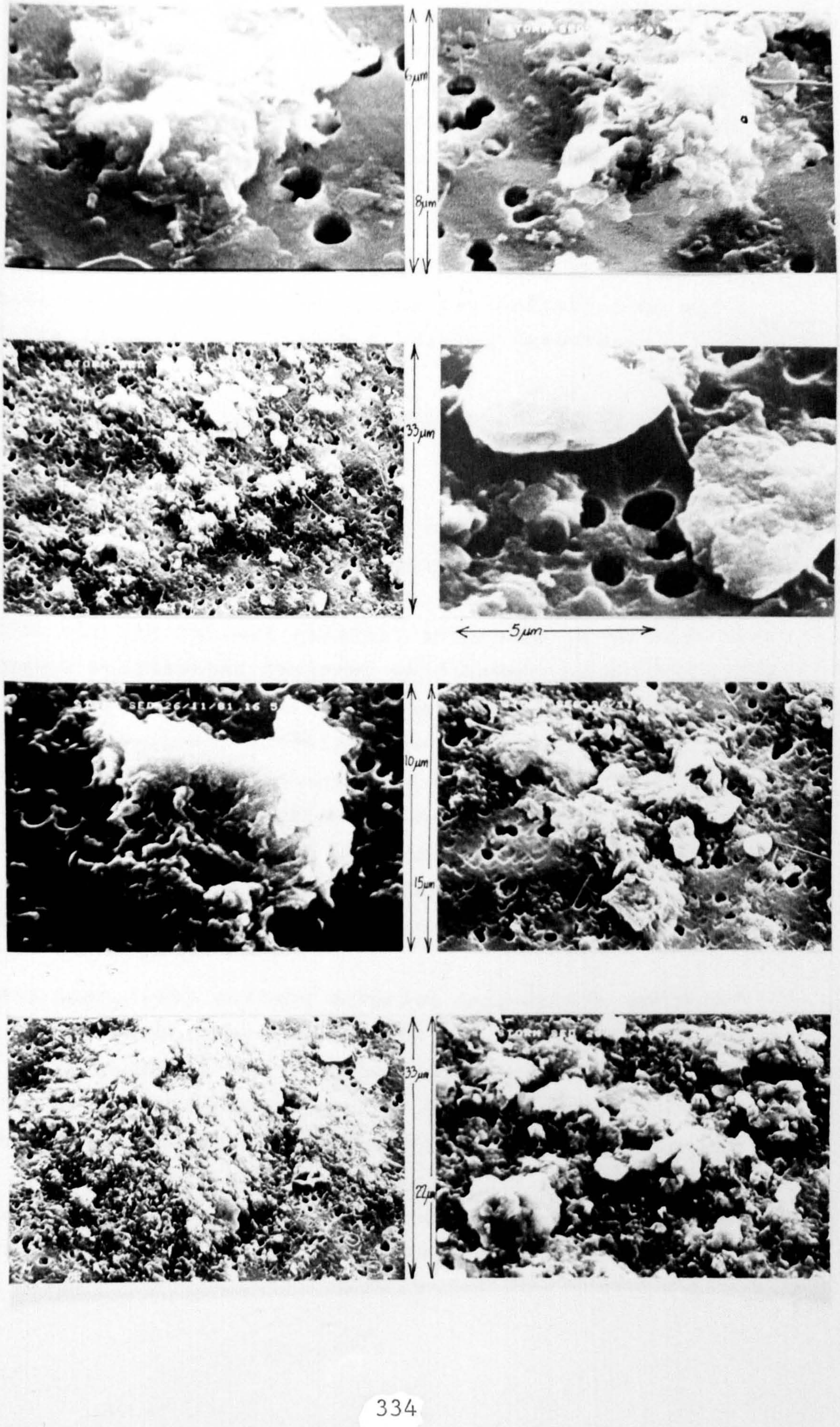
Plate 161 x 8800 Advancing silica precipitation and cementation of particles.

Plate 162 x 5900 Increasing aggregate formation, silica precipitation predominantly on individual particles, overall coat developing (centre).

Plate 163 x 2700 Substantial aggregate but largely of fine sediment due to low capacity of these storms.

Further Precipitation and Aggregate Development.

Plate 164 x 4000 A group of small aggregates and altered individual particles being incorporated; increasing silica coat.


6µm
8µm
33µm
5µm
10µm
15µm
33µm
22µm

material makes slow progress through the drain and the bulk of it only reaches the outfall late in the storm. With regard to the area of rainfall mentioned above, these storms cover much smaller areas of the catchment than those of other groups. Without an adequate rainfall monitoring network a full analysis of the entrainment patterns cannot be carried out.

During the later half of the storm there is a considerable increase in aggregation and silica precipitation on all particles (Sample 46, Table 8.5. Plates 164-171).

8.7. A Comparative Summary of Sedimentary Features in the Four Storm Groups.

Storm Group I stands out as being dominated by fresh-faced, angular sediment. The features are well-developed and cover large proportions of the particles. The storms are of short duration but the initial rainfall intensity is so high that it creates substantial sediment entrainment by scouring the land surface. The intensity of the rainfall and its collection of the fresh sediment outweighs the influences of the accumulation period and of the aggregated and precipitated material which may have been deposited during that time. The rainfall ceases almost as rapidly as it began leaving the drain thoroughly cleared of sediment which obviously did not have enough time for silica precipitation.

By comparison, fresh surface material only occurs in other storm samples about halfway through the storm. The gradual build up of rainfall and discharge to mid-storm peaks means that the drain is first cleared of aggregates and individual silica altered particles. Meanwhile the surface material is being washed towards the drain and follows the drain sediments to the outfall. The quantity of this sediment that is available and the degree of its alteration depends on the length of the

Plate 165 x 8000 Silica precipitation-solution surface; spherical particle with surface precipitation (→) confirming low flow.

Plate 166 x 8800 Typical small aggregate.

Aggregates of Increasing Size.

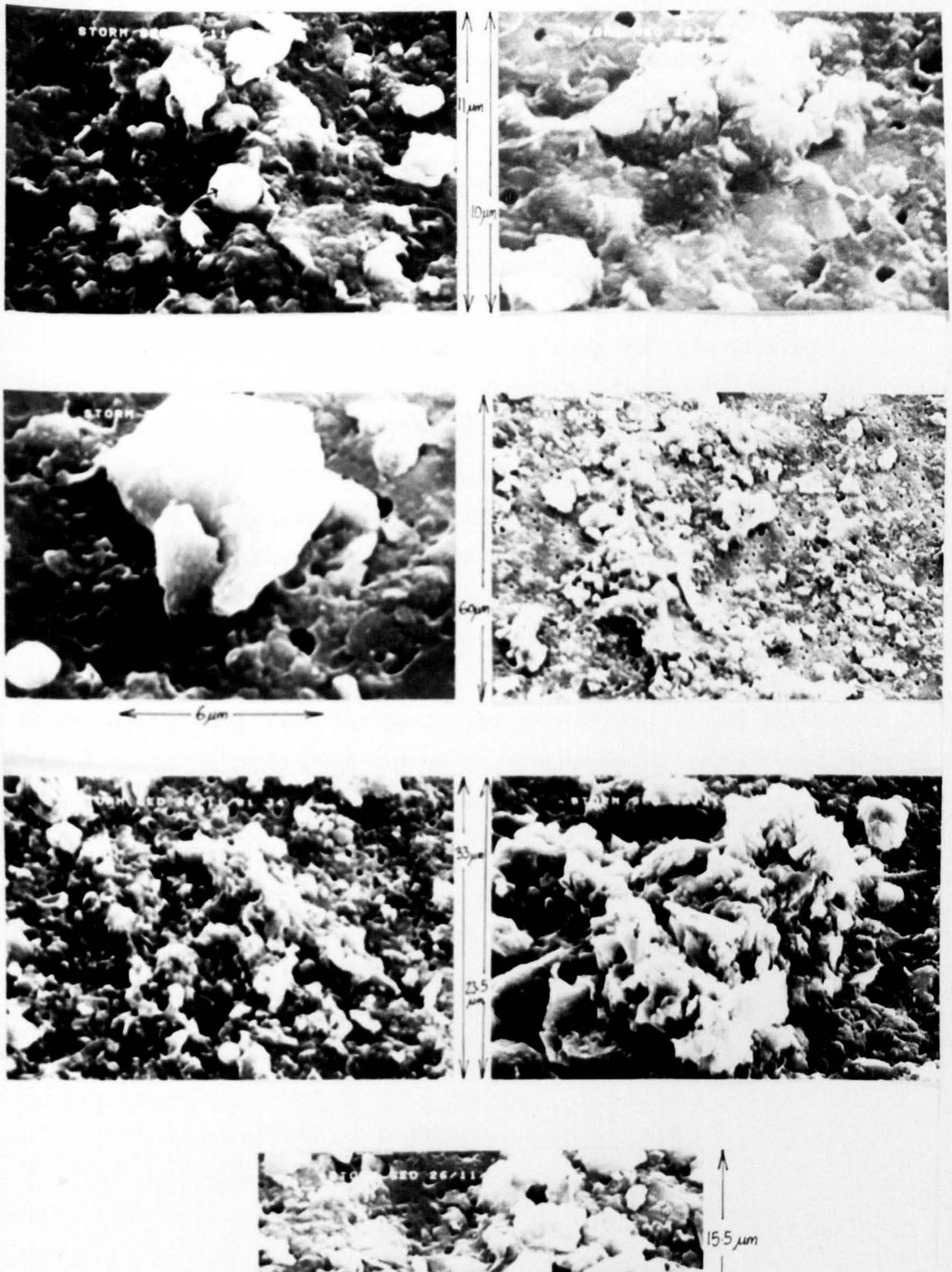
Plate 167 x 11900 Silica growth on individual subangular particle.

Plate 168 x 1500 Aggregate, well-developed with surface silica growth and incorporating further particles.

Plate 169 x 2700 Well-developed aggregate for this stage of any storm (after 4.5 hours) due to low flow, but small compared with final stage aggregates of higher flow and greater sediment load storms of Group II and III.

Plate 170 x 3800 Aggregate with outer area of relatively fresh sediments (→).

Plate 171 x 5700 Some remaining altered, individual particles clustering into an aggregate.


STORM
11 μm
10 μm
STORM
6 μm
6.0 μm
33 μm
23.5 μm
15.5 μm

antecedent dry period. Much of the material is considerably abraded and affected by silica precipitation from periods in stationary or slow moving gutter flow early in the storm. Storm Groups II and III are very similar in this respect although the quantities of sediment in Group III are smaller due to the lower rainfall and lower discharge capacity. The proportions of individual particles diminish towards the end of the storm during decreasing discharge due to both reduced input and their incorporation into aggregates. This sequence is only interrupted by late surges of rainfall and further surface sediment inputs. Further evidence of the rapid throughput of stormwater occuring during these Group I and Group II storms is the presence of diatoms which are observed in the Plates of the storms of 16.11.81, 17.11.81, and 10.10.81. As the tests are fragile and the animals require light and moisture only those kept undamaged in the darkness for a short time will survive.

Rainfall and discharge are so low in Group IV storms that often aggregates are too large to be carried. Slow flows encourage silica precipitation with the result that individual particles with precipitated silica predominate in these short storms.

CHAPTER 9

SIMULATED SEDIMENT ALTERATION.

9.1. Introduction and Aims of the Simulation.

9.1.1. Introduction.

The results of any study such as this, which by the very varied nature of the catchment and surrounding area are extremely complicated, demand some attempt at unravelling the processes operating on the sediment for a fuller understanding of the whole system. The most useful application of the results would be in the implications for comparable catchments. To determine how representative this catchment is, a number of others would also have to be monitored. However the examination of this catchment has been lengthy and the similar treatment of others would be time consuming beyond the confines of this study. Here, we are limited to the examination of component areas and processes of the catchment and to this end a number of experiments were contemplated. Ideally, it was hoped to seed the catchment with control sand of known surface texture and, from the controlled introduction and collection of sand through the catchment, to type the processes dominant at different points along the system. This would have had the outstanding advantage of attaching time periods to sediment travel. Eventually the details of such a project appeared unfeasible in particular because the tracers were fluorescent and their use would not be tolerated in such a public system. Also, as the tracer sediment would have been sand- rather than silt-sized the rates and mechanisms of movement would have been different and not directly comparable.

The results from the catchment, as they stand (Chapters 6, 7 and 8) provide comparisons of sediment size and surface texture across the land surface, along the drain and through storms but they are only relative since the original state of the sediment is unknown.

The simplest situation, at the head of the catchment, was particularly useful as a control area. The area is small (approximately 200m^2) and of a uniform style of modern housing with gardens. The surrounding land is an open space and therefore any outside sediment entering the drain will be soil material alone and of known characteristics (described in Chapter 7). The drainage pattern is a simple one comprising two tributary drains joining at 60° and thence combined to form the start of the main drain.

The sub-catchment can only be compared directly with similar areas of modern housing but the effect of the concrete driveways is to provide a relatively high level of silica which causes the unusually rapid aggregation of sediment. In this way the area is somewhat analogous to the whole catchment. The process of sediment accumulation, drain transport and increasing aggregation downstream (although here only as far as the next main sediment input) follows the overall pattern of sediment alteration through the catchment on a reduced scale. Silica precipitation and aggregation occur between the head of the catchment and the next sample point downstream but such rapid development was not seen between any other successive sample points and must be the result of the high silica availability in that area (as described in Chapter 7). The question of the time taken for the sediment to reach the next sample point, and hence the time taken to reach that state of aggregation under those conditions, can not be accurately determined without the recovery of tracer sediment. The rate of sediment transport is examined further in Chapter 10.

Consideration of the sub-catchment is useful in understanding the processes operating, and the effect of flow conditions on sediment characteristics, with a minimum of complications.

A number of reports can be found in the literature on the experimental production of quartz sand grain surface textures particularly on wind tunnel studies of eolian sediment (Kaldi et al 1978; Krinsley and Greeley, 1978; Mckee, Greeley and Krinsley, 1979). Krinsley and O'Hara (1976) and Lindé and Mycielska-Dowgiałło (1980), studied sediment in aqueous environments and the latter, especially, were at pains to simulate the motion of the natural river environment as closely as possible. They pointed out that suspended material in streams travels essentially at the speed of the flow and collisions and abrasion are minimal, and they tried to simulate the same situation. This is not such a necessary consideration in simulating the storm sewer system. The rapid turbulent flow, with levels often pipeful and surcharging, and high sediment concentrations generate severe particle impact and abrasion. In the open section of the flume used to simulate storm sediment transport some sediment was seen to travel in suspension at the velocity of the water but the high velocity, high sediment concentration and the period in the enclosed cylindrical pipe more closely simulated sewer pipeful flow. This flume system is a useful compromise in simulating sewer transport which in any storm includes both low-flow and pipeful stages.

The experiment described in this Chapter turns to the major processes operating in the catchment; those of turbulent channel and pipe flow and the effect on suspended sediment surface textures. From the simulated transport of control sand in a flume the surface textures were determined. By the elimination of these features from the study of drain flow surface textures (described in Chapter 7 and 8), the remaining features are attributable to other catchment factors.

All simulations such as this one are encumbered with their own problems and restrictions, particularly those due to scaling down. The most significant effect of scaling down the system from a channel the size of the drain to one the size of the flume was to increase the rate of particle collisions and hence the abrasion rate. Full details are given in Section 9.2.2 below.

In general however, the results go a good way to demonstrate the processes causing specific grain surface features, and in confirming the results of the catchment study. During the first 30 minutes of turbulent flow abrasion features are formed in abundance (described in Section 9.3.3.). From approximately 1 hour onwards sufficient quantities of free silica have been produced from abrasion to create precipitation features and particle aggregation (see Section 9.3.4.). This is the progression of events seen in the study of the catchment.

Further small scale experiments are described below in which an ultrasonic bath was used to try and simulate the abrasive conditions of sediment transport and link them to the resulting surface texture.

The flume trials provide results on the surface textures produced by flow transport. The remainder of the surface textures are specific to this urban catchment. The extent to which they are applicable to other urban catchments will depend on the land uses occuring in those catchments but as the majority of the sediment is road-derived (Chapter 7) considerable similarities can be expected.

9.1.2. Aims of the Simulation.

The aim of the simulation by flume trials was:

(i) To demonstrate the progressive formation of those surface textures and their increasing number and density produced by drainflow transport, and,

(ii) to distinguish them from those features attributed to the sediment origins of air, road, roof or land uses, and from features produced by other processes such as surface weathering, precipitation and solution.

9.2. Experimental Method of Flume Trials.

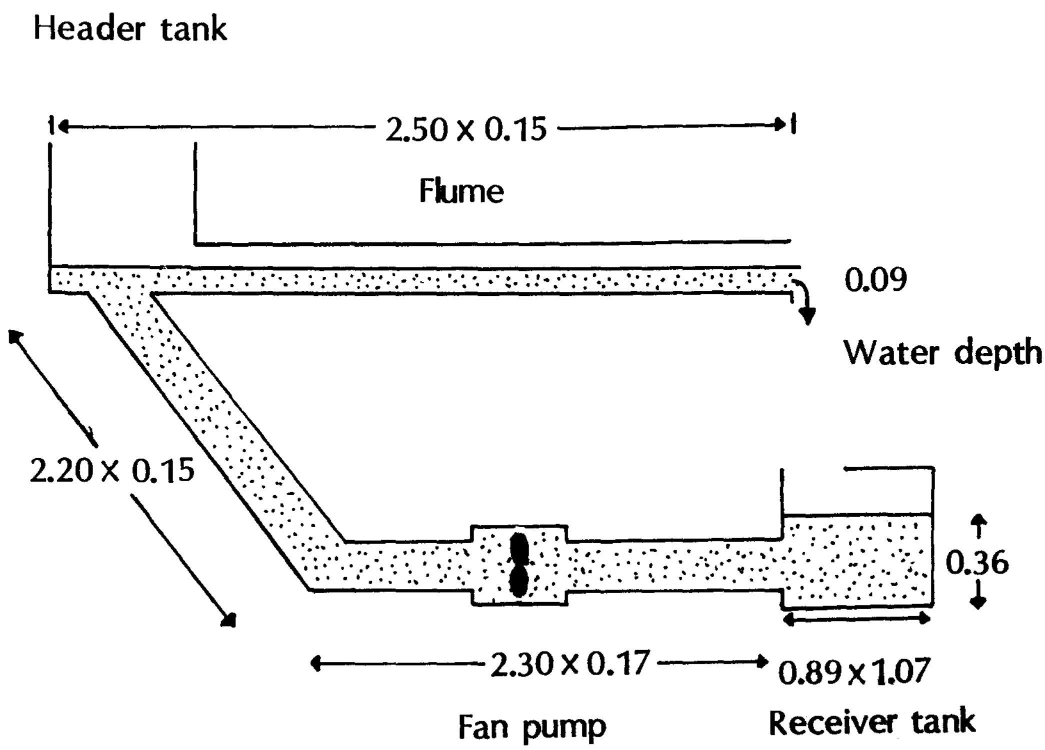
9.2.1. Equipment and Calibration.

The equipment consisted of a 2.20m rectangular recycling flume of 150mm width, fixed between header and receiver tanks. The tanks were in turn linked by cylindrical piping containing a splayed out fan pump which itself would not create any significant abrasion. A diagram of the equipment is shown in Figure 9.1. A manometer inclined at 55^o was attached for discharge measurement. The inclining of the manometer extended the difference in the height between the two levels and thus facilitated an accurate reading. The total volume of water in the flume system was $0.47m^3$ (468 l) which circulated at a depth of 90mm in the flume and at an average velocity of 0.53m/s. The discharge created was $0.00713m^3/s$ (7.134 l/s). The details of the measurements are given in Appendix 8.

Two types of sand were available for the flume trials in the approximate size range of the material sampled in the storm drain. One is a red fluorescent dye-coated sand ranging from 75µm to 210µm and the other an untreated white sand of between 90µm and 150µm. The majority of the sand introduced into the system was white as that had the smaller upper size limit which slightly more closely resembled the storm sediment. The red-coated sand was used more particularly to demonstrate the areas of preferential initial abrasion by obscuring the pattern of abrasion of the coating. The total weight of sand used was 250g and gave a sediment concentration of 534mg/l. The concentration was governed

FIGURE 9.1.

RECTANGULAR FLUME SYSTEM



Not to scale

Pipe dimensions: length x diameter, metres by the need to obtain a sufficiently large sediment sample for examination without significantly reducing the water volume. The concentration is of the same magnitude as the drain value (50 to 200mg/1) which was one aim of the experimental method in simulating the conditions of the drain as closely as possible.

9.2.2. Sampling Programme.

The sampling intervals were designed to capture the variety of abrasion features, the varying rates of abrasion and any periods of notable change in feature type.

The catchment storm durations ranged from 1 to 9 hours but the results of studies of these storms provided no guide to flume abrasion rates for two main reasons. First, the progress of abrasion during these periods was complicated when fresh inputs of material occurred and when those features present were masked by subsequent precipitation and solution features. Secondly, the effect of scaling down the system was likely to increase the rate of abrasion, as described in the next section.

A preliminary trial of sediment circulating in the flume and sampled at one, two and three hourly intervals showed that abrasion features were already present in large numbers after one hour and had largely given way to precipitation and solution features after two and three hours.

To follow the details of the formation of abrasion features the sediment was sampled at the following intervals: 1, 2, 5, 10, 15 minutes, then at 15 minute intervals until 3 hours had passed, this being the period of the expected highest abrasion rate. The reason for this expectation was that the flume abrasion rate was thought to be considerably higher than that of storms and even in the most intense storms of Group I the peak of abrasion has passed within one hour. Sampling was reduced to 30 minute intervals until the end of 5 hours of operation and thereafter reduced to hourly intervals until 9 hours were attained, it being hypothesised that sediment alteration would have reached a uniform rate during this time. Photographs were taken and texture analyses were done on a selection of these samples after a study of each of them showed the periods of greatest change. These included all the samples from the first hour where abrasion was dominant, five samples during the following 4.5 hours when abrasion and precipitation occurred, and on the sixth and eigth hours by which time precipitation and solution processes appeared to predominate.

9.2.3. Problems Involved in the Simulation of the Storm Sewer.

Every effort was made to simulate the stormwater system as closely as possible but inevitably a number of differences arose which affected the hydrological processes acting on the sediment.

Given the much reduced size of the flume system compared with the storm sewer most of the inadequacies of the model were due to scale.

In contrast to the small dimensions at the top of the catchment the drain diameter varies from 50mm to the diameter pipe and 1.5m x 2m rectangular outfall, 2000m downstream via increasing gradients. Clearly the velocity of the water in the storm drains varies with the different pipe gradients throughout the system and with the volume of water produced by different storms. However a design criterion of the storm drains is that they should be of sufficient gradient to generate a self-cleansing velocity, as described in Chapter 2. The velocity in the flume was maintained on average at 0.53m/s which, with the same sediment concentration as in the storm drain, produced a higher rate of abrasion through particle collisions. The features of abrasion are thus both more numerous and better developed during the first 15 minutes and 30 minutes of flume transport (Fuzzy values of impact pits of 3.0 to 3.[illegible] on 100% particles Table 9.2) than for comparable storm periods (Fuzzy values of 2.5 to 3.2 on 65 to 86% of particles, storm 16.11.81. Table 8.1) for the most intense storms of Group I.

The overall trial time encompassed the range of storm durations recorded but abrasion and aggregation occurred in much shorter periods than during storms. The advanced development of aggregates which is seen in the drains is however limited in the flume by the continuous comparatively high discharge for the sediment concentration, as described in Section 9.3.4.

The sediment size is more of a scaling up problem. The finest control sediment available which was relatively unaltered and of known size was at best twice the size of the majority of the storm sediment sampled, and reached up to over five times that size. It has been suggested in the literature that fine sediments such as those suspended in stormwater produce different surface textures than sediment sizes of a higher magnitude. However the surface textures observed on the control sand appear to be of the same type as those on the stormwater sediment. The difference is that the flume sediment is more uniform and the features better-developed and generally larger mainly because the sediment is less adulterated by other processes such as act on the catchment sediment.

The nature of the flow in the flume is constant but that of the storm sewer varies according to the volume of water present. The water level in the flume was maintained at a constant height and the sediment was carried in turbulent flow. The samples were taken in the upper half of the flow where all the sediment was in suspension as opposed to lower down where some grains were seen to be saltating. The suspended sediment collected from the outfall is similarly travelling suspended in turbulent flow. However, along the drain the water level often rises to the pipeful stage and when the water is under pressure this causes surcharging. Although surcharging may influence the surface textures no details have been described and no features found on the storm sediment have been linked to surcharging. The lower pipe section of the flume conveys the water and sediment at pipeful flow but high pressure does not build up in this open flume system and because the surface textures are so similar to those produced in the storm drain any influence of surcharging in the drain appears to be minimal.

9.3. Simulated Surface Textures.

9.3.1. Introduction.

The methods of examining the sediment surface textures produced in the flume, and of analysing the photomicrographs, was the same "Fuzzy-score" method which was described in Chapter 7 and applied in Chapters 7 and 8. The method was used both to describe the control sand and the sand circulated in the flume, and to produce mean feature scores and percentages of particles per feature. The results are used to demonstrate the progressive alteration of the sediment with the increasing period of simulated transport.

Simulated sediment alteration was in three stages:

(i) That sediment suffering maximum abrasion within the first hour of transport;

(ii) sediment undergoing both abrasion and surface precipitation during the following 4.5 hours;

(iii) the dominance of silica precipitation and solution during the last three hours of the trial.

The time intervals are only as precise as the sampling intervals. Having attached these approximate times to periods of feature development a repeat of the experimental methods would be necessary with more frequent samples taken during those periods of change estimated above. It is important to note that this would require the complete emptying and cleaning of the flume and the introduction of new sand. Any sand left in the flume that has circulated previously would impair the results. As the experimental periods of change could not be directly related to the catchment because of differences due to scaling down, this lengthy procedure was not undertaken.

Throughout the simulation the dominant features produced at any stage occurred in large numbers on almost every particle examined, the degree of development depending upon the length of time for which the process had been operating (shown in Tables 9.2. and 9.4.). All other features were therefooe few, and small, or absent altogether as demonstrated by the lack of middle range results in Tables 9.2 and 9.4. In a natural system results such as these would be a clear method of recognising a sediment with certain well-defined features denoting one source and a limited transport history. The number of processes acting on the sediment in the flume is limited by the controlled conditions of the flume and the suites of features present arise from those processes. This is in distinct contrast to the stormwater sediment. Some features on stormwater sediment do occur dominantly but the presence of a range of features demonstrates the very varied combinations of sediment source, runoff and drain transport histories and the texture alteration all these conditions impose.

9.3.2. Surface Features of the Control Sediment.

A study was made of the sand grains before their introduction into the flume, to act as a control during the examination of the effects of flume transport on the sediment. The photomicrographs of both the coated and non-coated sand are given in Plates 1 to 16, and the Fuzzy Analysis in Table 9.1.

The sand in the size range 75μm to 210μm is subangular or moderately well rounded (Plate 1) and had been dyed in a fluorescent red dye which coated the particles in a smooth featureless layer overlying the true particle surface. Abrasion of the coating occurs preferentially first on protruberences and particle edges and lastly in hollows which are protected from abrasion (Plates 1-7). The order of preferential abrasion provides grounds for supposing that the abrasion of particle surfaces follows the same pattern. In the case of the dyed particles however, there are some small areas which may have escaped being dyed, for example on the particle shown in Plate 7.

The majority of the exposed surfaces are considerably rounded and pitted, either by abrasion or solution or a combination of the two. (Plates 5-7). Unfortunately the details of the sediment history of these grains are unknown and in particular whether the size range was obtained from grinding and, or, sieving. The pitted but well-rounded surface however is recognisable and abrasion marks found in that surface after the trials can be attributed to flume transport.

The sand in the range 90 to 150μm tends to be subangular but with rounded edges and corners (Plates 8-16). The surfaces are in some cases fairly irregular with angular protruberences (Plate 11), steps, cracks, large and small impact pits, many fine adhering particles throughout and possibly precipitation and solution surfaces. The fine adhering material may be the result of the method employed to acheive the specified size range but again, the method is unknown. The more rounded areas of the particles have surfaces of lower relief (Plates 14-16). The features seen on these particles are uni-directional and are very similar in appearance to those described

Red Dye-Coated Control Sand (75-210μm)

Plate 1 x 113 Overall view of subangular and subrounded particles wholly or partially coated in red dye.

Plate 2 x 550 Detail of coated particles showing thinning of coat on protruding areas of particles and on some edges (→), revealing rounded, pitted abrasion and solution surface beneath.

Plate 3 x 550 Well-coated particle with adhering surface fragments and small cracks in coat.

Plate 4 x 1500 Detail of Plate 3 showing broken area of coat and weathered particle surface beneath.

Plate 5 x 900 Detail of sub-rounded particle with coating thickest over depressions, thinning over protruding area (top centre) and broken on r.h.s. Revealed beneath is abraded surface strongly affected by solution, especially along lines of weakness.

Plate 6 x 680 Edges and protruberances exposed by abrasion before hollows revealing well-rounded abrasion and solution surface beneath.

Plate 7 x 3000 Details of Plate 6 showing particle surface and limit of coating; rounded, thinned limit of coating suggests liquid dye only reached this far, rather than the sharp edges caused by abrasion.

Untreated Control Sand (90-150μm)

Plate 8 x 120 Overall view of subangular and subrounded sand grains.

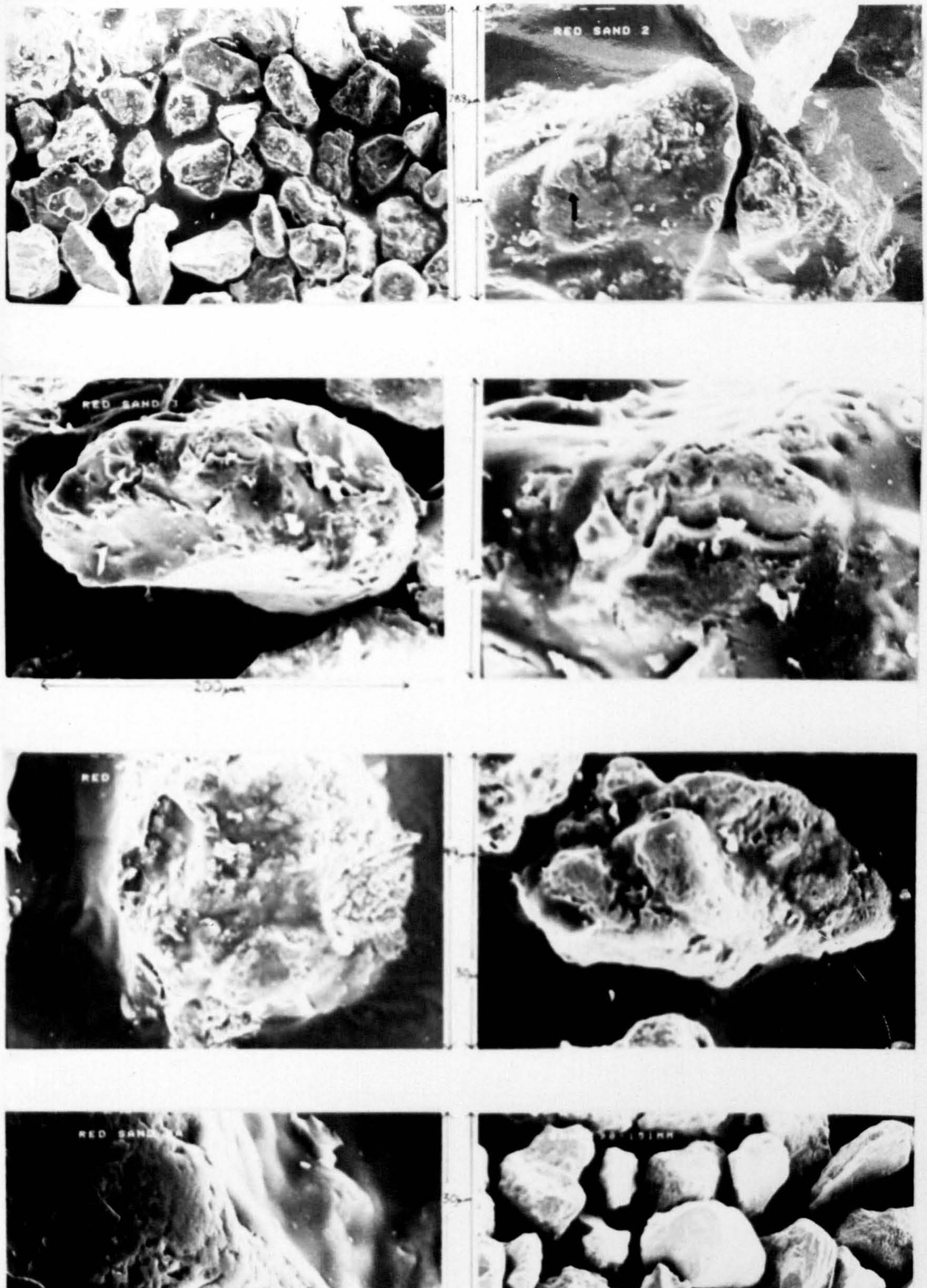

RED SAND 2
RED SAND 3
200μm

Plate 9 x 280 Reduced view of control sediment showing both smooth and weathered surfaces.

Plate 10 x 600 Weathered particle surfaces with impact pits modified by solution. Frequent fine adhering fragments may result from sieve sizing.

Plate 11 x 890 Eroded surface, pitted by solution, with preciitation and adhering particles..

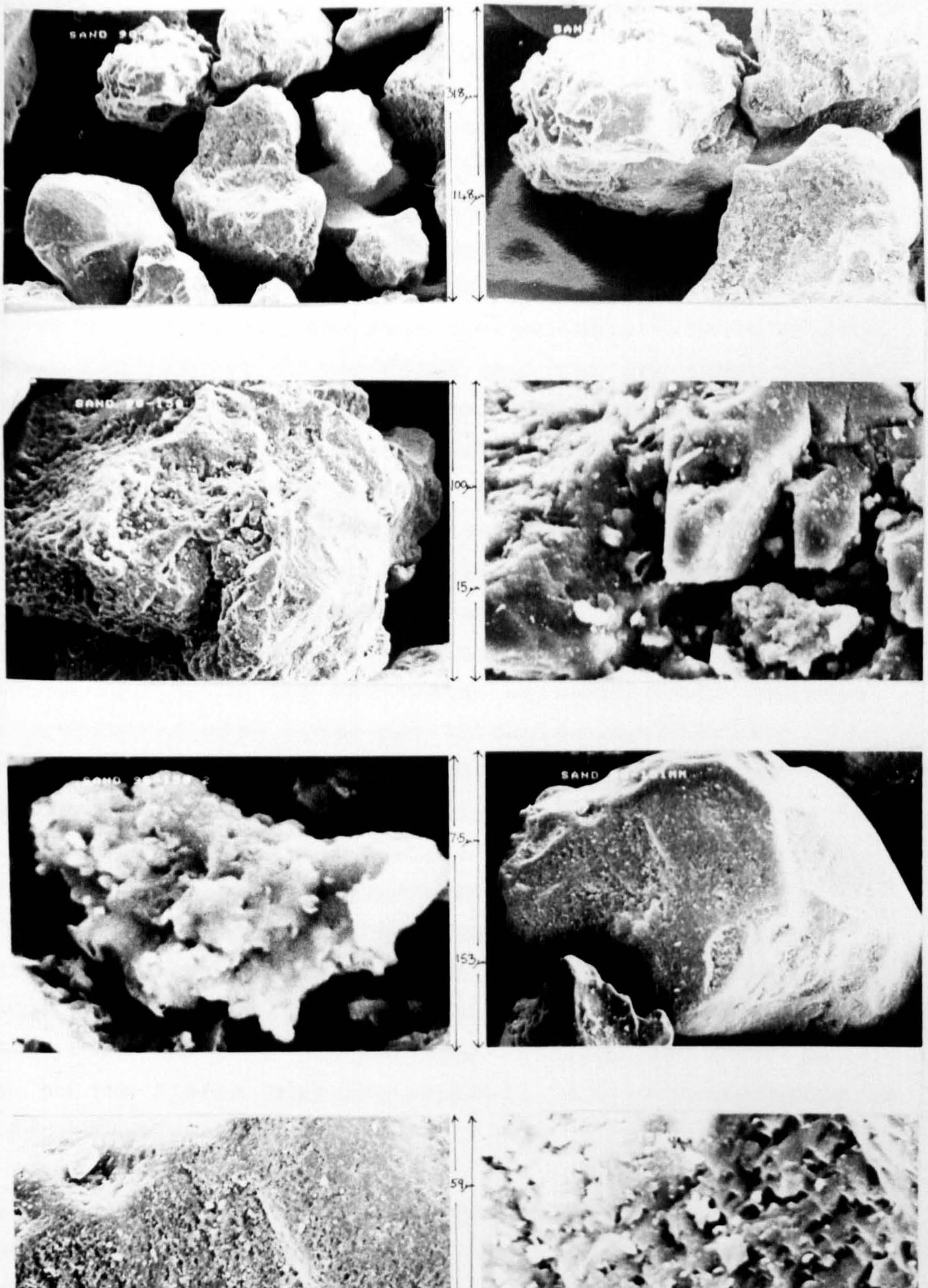
Plate 12 x 5800 Detail of Plate 11; irregular surface with early precipitation and solution, cracks, impact pits and adhering fragments.

Plate 13 x 12000 Detail of Plate 12: precipitated silica covering a small prodruding area of the particle surface.

Plate 14 x 580 Surface impact pits of 1-20μm include 'V' motches (lower right), mechanically formed of side 10μm, and striations (upper right).

Plate 15 x 1500 Detail of Plate 10 showing fine, orientated solution features and adhering fragments.

Plate 16 x 8700 Detail of Plate 15 showing unidirectional orientation of quartz dissolution features.


318μm
11.8μm
109μm
15μm
75μm
153μm
59μm
10μm

as quartz dissolutional features by Wilson (1978, 1979).

9.3.3. Simulated Sediment Erosion.

Erosion of the trial sediment was the dominant process in the flume during the first 30 minutes of its operation. Thereafter. precipitation and aggregation developed considerably as described in the next section. At the beginning of the first 30 minute period abrasion is very clearly the most dominant process but the effects of solution are seen increasingly from 15 minutes onwards. The results of the Fuzzy Analysis are shown in Table 9.2. but are a slightly weaker measure of particle features for the trial sand during this first stage than they are for the aggregates seen later and for the stormwater sediment. The Fuzzy Analysis describes the abrasion features well but the presence of the coatings and distinct solution features in the particle surface are obscured. The features: smooth coat and solution hollows, were listed in the detailed feature list of Table 7.1. On the stormwater sediment these features commonly occurred with other precipitation and solution features and were classified accordingly in the list of amalgamated features for Fuzzy Analysis (Features B and C, Table 7.3.). In this section the control sediment and simulated features would perhaps be better defined by the original descriptions. However, on the whole the Fuzzy technique described the experimental sediment fully and provided results consistent, and easily comparable with, those of stormwater sediment. The coatings and solution features are shown so clearly on the Plates that any possible lack of description is well compensated.

Examining in detail the control sediment after the first minute of flume transport has shown that relatively small, irregularly shaped particles are carried at this stage. Maximum particle diameters measured range from 10 to 17μm which is considerably smaller than the 75 to 210 μm diameters of the red coated sand and the 90 to 150 μm of the white control sand. It appears that during this first minute the discharge capacity has not reached its full strength. The sediment sampled (Plates 7-22) was of low concentration and bears little similarity to the control sand (Plates 1-16). The particles are well altered by abrasion, precipitation and solution and are assumed to be extraneous fragments from the bulk of the sample sediment.

After 2 minutes of flume transport the sediment sampled is recognisable as the control sand grains (Plates 23-27). The remnants of the coating in protected hollows and cavities of the particle surface indicate the extent to which the force of abrasion has removed the rest of the coating during this short period. A prolonged session in the ultrasonic bath created impact pits in the coated particles but by no means removed the coating. This may appear surprising in the light of the severe nature of the ultrasonic bath motion. It therefore points to the processes of abrasion in the flume being particularly strong. It must be noted however that the different effects on the particles may be the result of the different forms of motion. In the bath the particles move rapidly in all directions whereas in the unidirectional flow of the flume the particles move in a rotational manner. The latter appears the more rapid method of abrading particle edges. A further comparison of the flume and the ultrasonic bath with the stormwater system is given below in an attempt to elucidate the processes involved.

After 5 minutes impact pits are abundant and well-developed (Fuzzy value 3.0, 100%, Table 9.2.). The coatings have largely disappeared (Plates 28-33) revealing fine solution surfaces which are particularly evident in the slightly more rounded white sand grains. Precipitation of a "granular" form (see below) of approximately 1 to 10 μm diameters occurs on and around these particles and probably formed on fine abraded fragments which

TABLE 9.1.

FUZZY ANALYSIS OF CONTROL SEDIMENT SAMPLES

Sample Feature	Red Sand (75-210μm)		White Sand (90-150μm)	
	μ	%	μ	%
A. Aggregates @				
B. Si Precipitates	2.4	85**	1.5	100**
C. Pitting	3.0	73*	3.6	100**
D. Fresh Face	1.9	56	2.1	83**
E. Angularity	3.1	98**	3.6	100**
F. Steps	2.4	54	2.0	46
G. Impact Pits	3.5	100**	3.5	100**

@ Feature list given in Table 7.3

μ = Mean Fuzzy value of feature from particle sample

% = Percentage of particles with feature.

71* = Notable values 70-79.

100** = High values 80-100.

TABLE 9.2.

FUZZY ANALYSIS OF CONTROL SEDIMENT: 1–30 minutes.

Sample Feature	1 min		2 mins		5 mins		10 mins		15 mins		30 mins	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A. Aggregates @	3.0	25					3.0	50				
B. Si Features	2.1	100**	2.6	83**	2.8	71*	2.5	100**	5.0	100**	3.8	100**
C. Pitting	2.6	63	3.5	100**	4.4	71**	2.6	83**	3.5	80**	4.0	20
D. Fresh Face	3.0	75*	1.0	17	2.0	28	2.8	66	1.3	60	3.5	60
E. Angularity	3.0	100**	2.5	100**	2.7	100**	3.7	100**	3.4	100**	3.8	100**
F. Steps	2.0	25	2.0	33	1.0	14	2.0	17	1.5	40	2.0	40
G. Impact Pits	2.8	100*	3.0	100**	3.0	100**	3.2	100**	3.6	100**	3.0	69

@ Feature list given in Table 7.3.

μ = Mean Fuzzy value of feature from sample particles.

% = Percentage of particles with feature.

71 * = Notable values 70–79.

100** = High values 80–100.

Flume Transport, 1 Minute: Variety of First Sediment Sampled.

(Nucleopore filters, circular apertures approximately 0.5μm diameter)

Plate 17 x 5400 Irregular jagged edge and surrounding pieces suggest breakage on filtering (l.h.s). Granular, loosely adhering precipitate on particle, r.h.s.

Plate 18 x 5700 Subangular particle with severe abrasion and solution on edges and precipitation developing on upper protrusion.

Plate 19 x 8700 Particle with abraded edge; fresh-face with impact pits and adhering particles; precipitation devoloping (right) and cementation (upper left).

Plate 20 x 5600 Aggregate comprising fresh-faced angular particles cemented together but with little sign of surface precipitation.

Plate 21 x 8500 Small aggregate of rounded particles with surfaces of small solution hollows and again, little precipitation.

Plate 22 x 8700 Subrounded particle with fine granular surface precipitates on irregular abrasion-solution surface of low relief (0.1 - 0.2μm).

2 Minutes: Widespread Remnant Surface of Trial Sediment.

Plate 23 x 880 Eroded surface, assumed to be pre-coating (similar to control grains), remnant coating in hollows.

Plate 24 x 580 Coating remnant on particle (→); irregular abrasion solution surface, pits hollows and adhering fine particles.

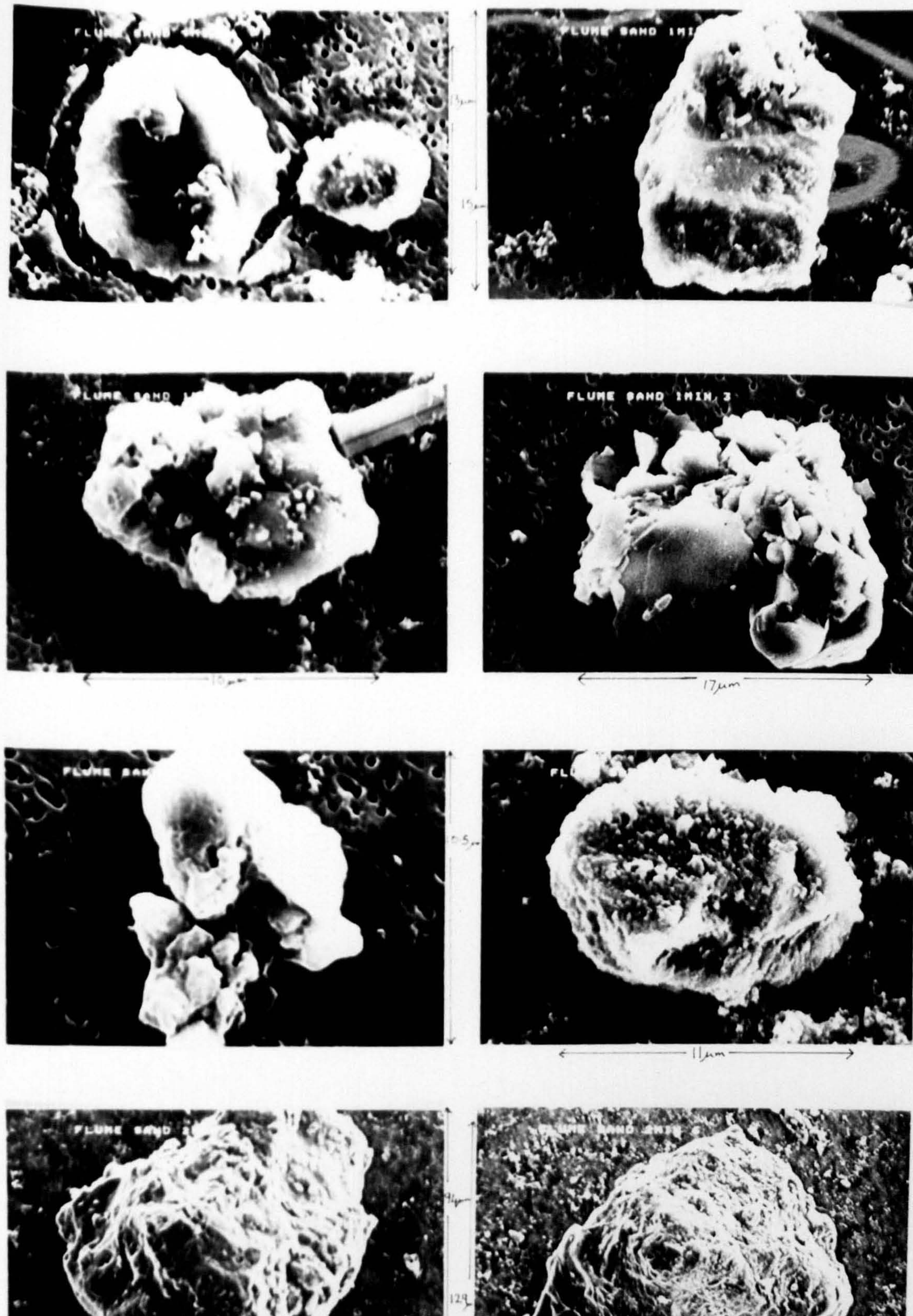

17µm
11µm

Plate 25 x 880 Well-rounded particle with abrasion-solution surface, solution concentrated in hollows, away from abrasive activity.

Plate 26 x 570 Irregular, subrounded particle; pitted and cracked surfaces with rounded large (17.5μm) and small (3.5μm) 'V' notches. (→)

5 Minutes: Reduction of Coatings

Plate 27 x 1190 Subangular particle with precipitation-solution surface, edge erosion masked by precipitation.

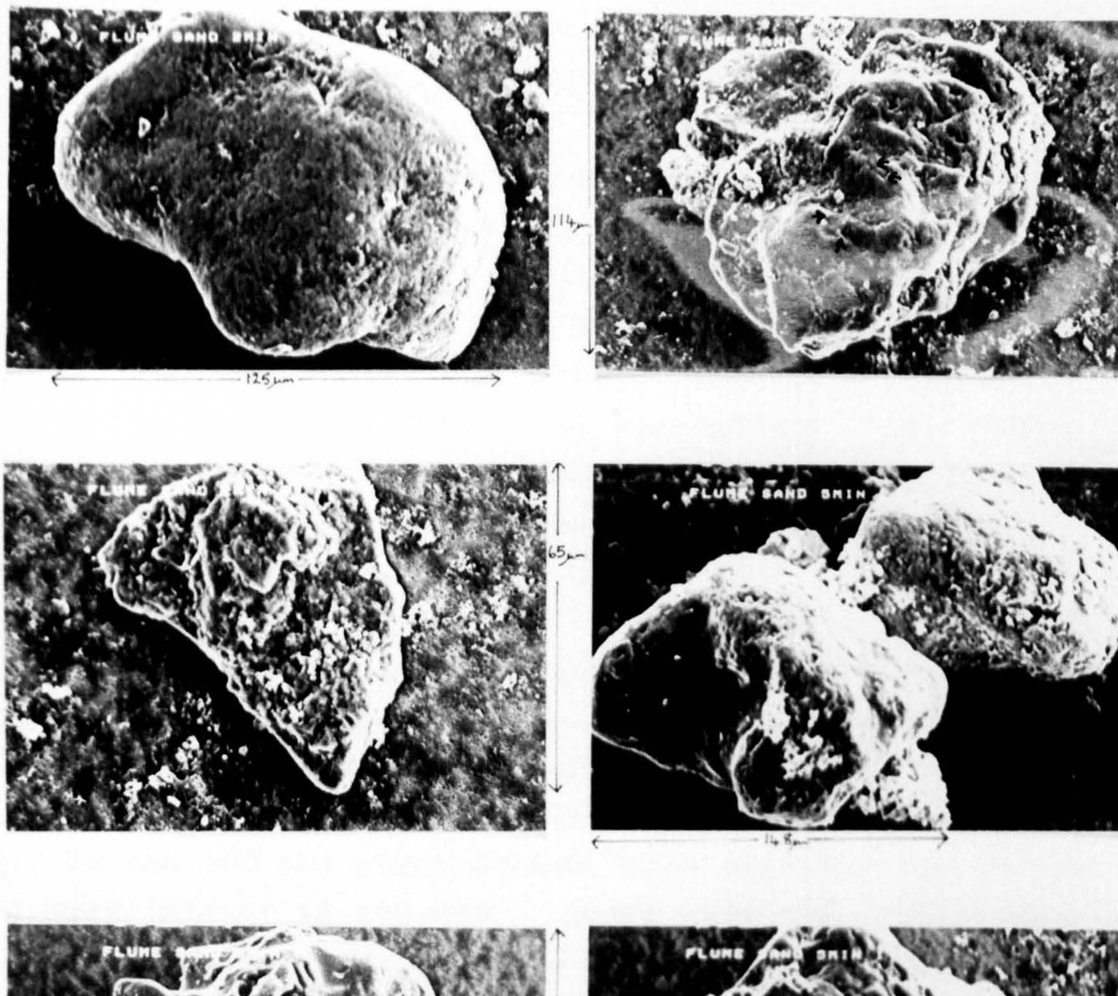
Plate 28 x 580 l.h.s. intact coating in protected cavity, exposed surface of control sand. R.h.s. coating restricted to crevices, adhering fine particles and loosely adhering precipitated silica.

Plate 29 x 620 Almost entire coating remains probably due to particle becoming lodged in protected area of system; l.h.s. fresh-face indicates abrasion of particle and coating; r.h.s. coating removed exposes control grain surface.

Plate 30 x 580 Subangular particle with severe abrasion especially on lower edge. Irregular surface of pitting and solution hollows, and rounding of edges and corners both by solution and early precipitation.

Plate 31 x 630 Angular particle abraded at lower end; early precipitation on most faces. Step features and solution pits concentrated (top left).

Plate 32 x 630 Rounded particle with solution surface and more extensive solution in cavities; granular precipitates adhering.


125 μm
114 μm
65 μm
148 μm
113 μm
201 μm
141 μm

act as precipitation nuclei. The fine fragments will have been created by abrasion and adhere to large particles in increasingly large numbers as time goes on.

Precipitated silica is shown in one of two different forms on all particles to some extent by the end of 10 minutes (Fuzzy value 2.5, 100%, Table 9.2) (Plates 34-38). The two types: "granular" (Plates 32, 34) and smooth (Plate 35) are described fully in Section 9.3.4 when, later in the trial, they occur in abundance. The first aggregation of particles occurs at this stage (Plates 37 and 38) which, after just 10 minutes, is considerably sooner than in storm sediment as shown in Table 9.3.

The sediment sampled after 15 minutes (Plates 39-44) tended to be angular with irregular abrasion-solution surfaces with solution being particularly dominant (Plates 42 and 44). Areas of coating have still survived in a few isolated examples (Plated 39 and 40) and precipitates, both granular and smooth can be seen (Plates 42 and 43). Impact pits are present on all the flume sediment (100%,Table 9.2.) and increased in development with time from a Fuzzy value of 2.8 to 3.6 during the first 15 minutes.

By the end of the 30 minute period (Plates 45-48) precipitation is beginning to occur all over the particles and to suffer corrosion by solution. The high rate of abrasion thus far will have released the silica which now goes into the make up of precipitates. With the development of solution and precipitation features there is a corresponding drop in the percentage of particles with impact pits from 100% after 15 minutes to 60% after 30 minutes (Table 9.2)

Little resemblence is seen between the textures or shapes of the particles now and the original form of the control sediment, mainly as a result of abrasion and solution processes.

TABLE 9.3.

A COMPARISON OF INITIAL AGGREGATION TIMES BETWEEN SIMULATED AND STORMWATER TRANSPORT.

Transport Conditions	Time Until Aggregation
Flume	10 minutes
Storm I (16.11.81)	1.46 hr.
Storm II (10.10.80)	3.06 hr.
Storm III (14.11.80)	6.13 hr.
Storm IV (26.11.80)	4.13 hr.

10 Minutes: Early Precipitation Features.

Plate 33 x 1190 Severe solution of particle surface, separate precipitate growth in globular form.

Plate 34 x 6300 Fresh-faced, angular particle with steps 'V' notches; adhering particles and separate precipitate development; small granular precipitates also loosely adhering to particle surface.

Plate 35 x 1500 Particle of both fresh-faces with impact pits and rounded surfaces with solution hollows; precipitation growing from particle, and on surrounding granular material.

Plate 36 x 1600 Widespread precipitation on particle as well as fresh and abraded faces and loose granular sediment.

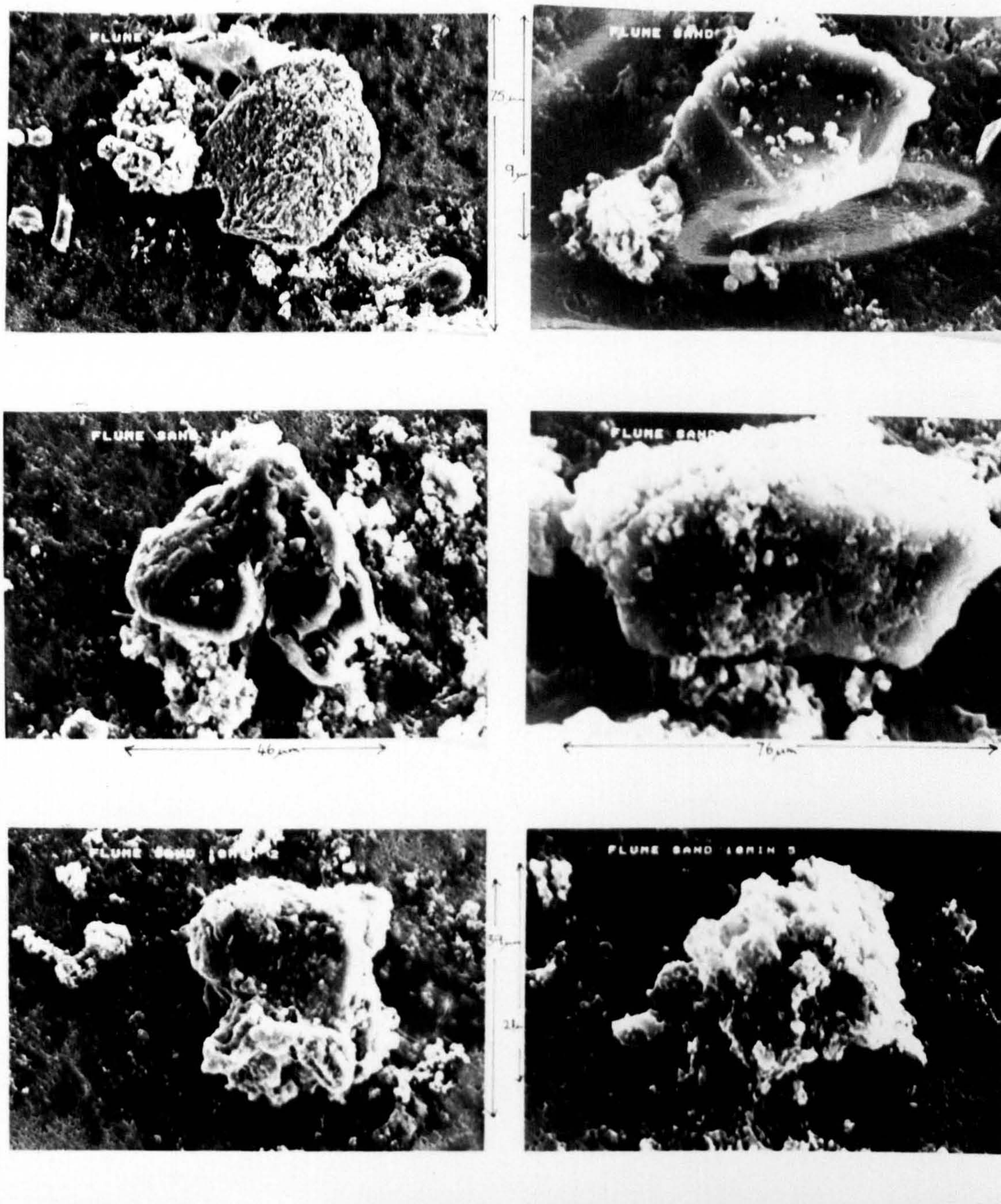
Plate 37 x 1600 Early aggregation on particles with silica precipitation.

Plate 38 x 2900 Precipitation concentrated on protruding surfaces and attacked by solution.

15 Minutes: Dominamt Solution Surfaces.

Plate 39 x 420 L.h.s. dye-coated areas survived but particle surface is predominantly abraded and has adhering fragments; r.h.s. angular particle with abrasion-solution surface.

Plate 40 x 4300 Detail of Plate 39 showing thin dye-coating over irregular abraded surface.



FLUME
FLUME SAND
75µm
9µm
46µm
76µm
FLUME SAND 10MIN 5
21µm
212µm
SAND 15 MIN

Plate 41 x 970 Angular particle with upper abraded solution surface and smooth precipitate growing from particle; loose granular precipitate (centre front).

Plate 42 x 1600 Detail of Plate 41, finely abraded surface affected by solution. Charging of granular particle, or precipitate, (foreground) indicates loose connection with substrate.

Plate 43 x 970 Abraded, angular particle with step features and irregular abrasion, precipitation and solution features in cavities, also smoother faces of fine abrasion-solution features and spread of low relief precipitation.

Plate 44 x 1310 Subangular particle with striations and steps across abrasion-solution surface, possibly relict control sand surface. Edge area (lower right) shows solution hollows below general level of particle surface.

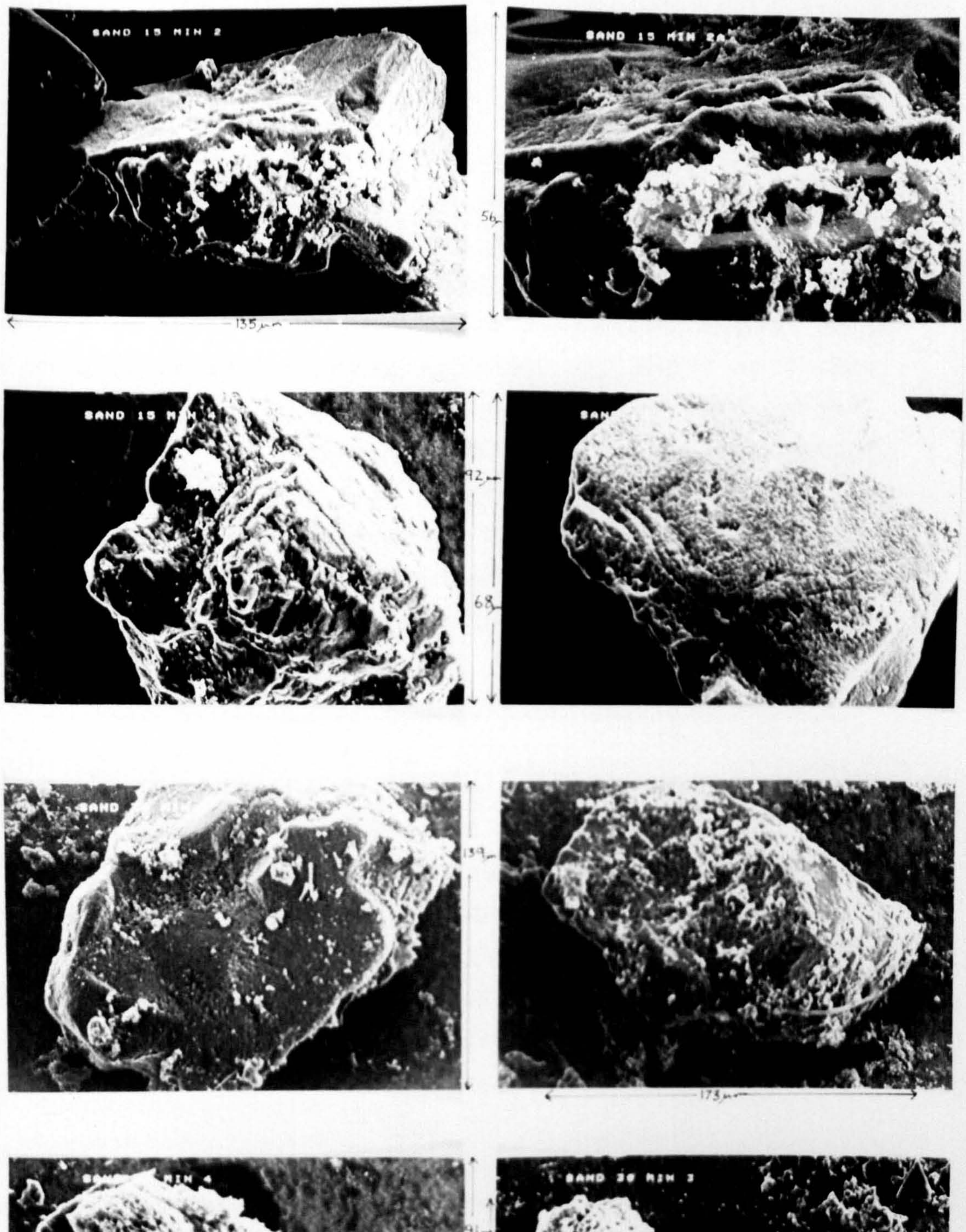
30 Minutes: Increasing Precipitation and Solution Features.

Plate 45 x 640 Subangular particle with abrasion-solution surfaces, solution most active in protected hollows; abrasion features include steps and striations; fine particles adhere.

Plate 46 x 640 Subangular particle with abrasion-solution surface of high relief (1.5µm hollow depth) and considerable loosely adhering, surface precipitation.

Plate 47 x 980 Precipitation widespread over particle surface, severely attacked by solution.

Plate 48 x 430 Well-developed precipitation-solution surface also with granular precipitation; adhering particles are increasingly common.


SAND 15 MIN 2
135μm
SAND 15 MIN 2a
56μ
92μm
68μ
139μm
173μm
SAND 30 MIN 3

In this last sample the spread of precipitation is seen in the early stages and marks the end of the dominance of abrasion and solution.

The patterns of abrasion features corresponds well with those found by Lindé and Mycielska-Dowgiałło (1980). However their method did not simulate the processes of silica precipitation although they acknowledge it occurs in streams. The motion of their flume simulated multi-directional movements as well as allowing the sediment and water to follow along the cylinder. The sediment was considerably larger (0.031 to 8mm) than the stormwater sediment and was allowed to run for 1000 hours. The lack of precipitation and solution features in that time is probably due to the much lower sediment concentration of 0.0003mg/l compared with 0.3370mg/l in the flume under discussion in this study.

9.3.4. Simulated Erosion, Precipitation and Aggregation.

The most significant change in the sediment with time, after the first 30 minutes, is the onset of widespread aggregation. (Table 9.4.) Precipitation has developed sufficiently to incorporate sediment and the proportion of aggregates increases steadily with time until 100% is attained after 4.30 hours and remains so thereafter. The size of the aggregation is limited however after 4.30 hours as described below, and confirms the continuing influence of strong abrasive forces.

After 1.15 hours silica precipitation of low relief and with a smooth surface affected by solution has spread over particle surfaces and fine particle fragments. (Plates 49-54). Many particles are already cemented to a few others in the early stages of aggregation which was also seen in a few instances in earlier samples. It is of interest to note that in the flume the only source of silica for precipitation is the particles in the trial, whereas in the stormwater sewer it may also be

TABLE 9.4.

FUZZY ANALYSIS OF CONTROL SEDIMENT: 1-8 HOURS.

Sample Feature	1.15 hrs.		2 hrs.		2.45 hrs.		3.45 hrs.		4.30 hrs.		6 hrs.		8 hrs.	
	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%	μ	%
A. Aggregates@	3.0	40	3.4	78	3.0	20	2.7	30	3.5	44	3.0	22	2.7	43
B. Si Features	3.9	80**	3.8	89**	4.5	80**	3.2	90**	2.9	100**	3.2	100**	2.6	100**
C. Pitting	2.6	70*	2.8	44	2.5	40	2.4	50	3.0	56	2.3	78*	2.0	86**
D. Fresh Face	2.9	80**	2.4	56	3.5	60	3.3	80**	2.9	100**	2.8	89**	3.0	86**
E. Angularity	3.1	80**	3.2	67	3.0	80**	2.9	80**	3.5	89**	3.4	78*	2.6	71*
F. Steps	2.0	40	2.0	11			2.5	20	1.6	56	3.0	33	1.0	14
G. Impact Pits	3.2	60	2.6	78*	3.5	80**	2.9	70*	3.1	100**	3.0	89**	3.6	71*
I. Clays			5.0	11										

@ Feature list given in Table 7.3
μ = Mean Fuzzy value of feature from sample particles.
% = Percentage of particles with feature.
71* = Notable values 70-79.
100** = High values 80-100.

1.25 Hour: Spread of Precipitation.

(Nucleopore filters, apertures approximately 5µm diameter).

Plate 49 x 8700 Fresh-faced subangular particle; well-developed steps, straight and conchoidal 'V' notches, circular solution lollows; angular edges unusually having escaped rounding by this stage but adhering precipitates are present.

Plate 50 x 2600 Widespread early granular silica precipitation and solution of protruding fresh-face (top left); increasingly common square or cubic crystals, possibly of salt (NaCl) of 1-2µm surface.

Plate 51 x 2700 Irregular particle of fresh faces with extensive early development of silica precipitation and overlying cubic crystals, possible formed on sample drying.

Plate 52 x 8700 Detail of Plate 51 showing angular fresh faces but minimal edge abrasion; silica precipitation (left) appears to have formed from particle surface but is more separate in upper part.

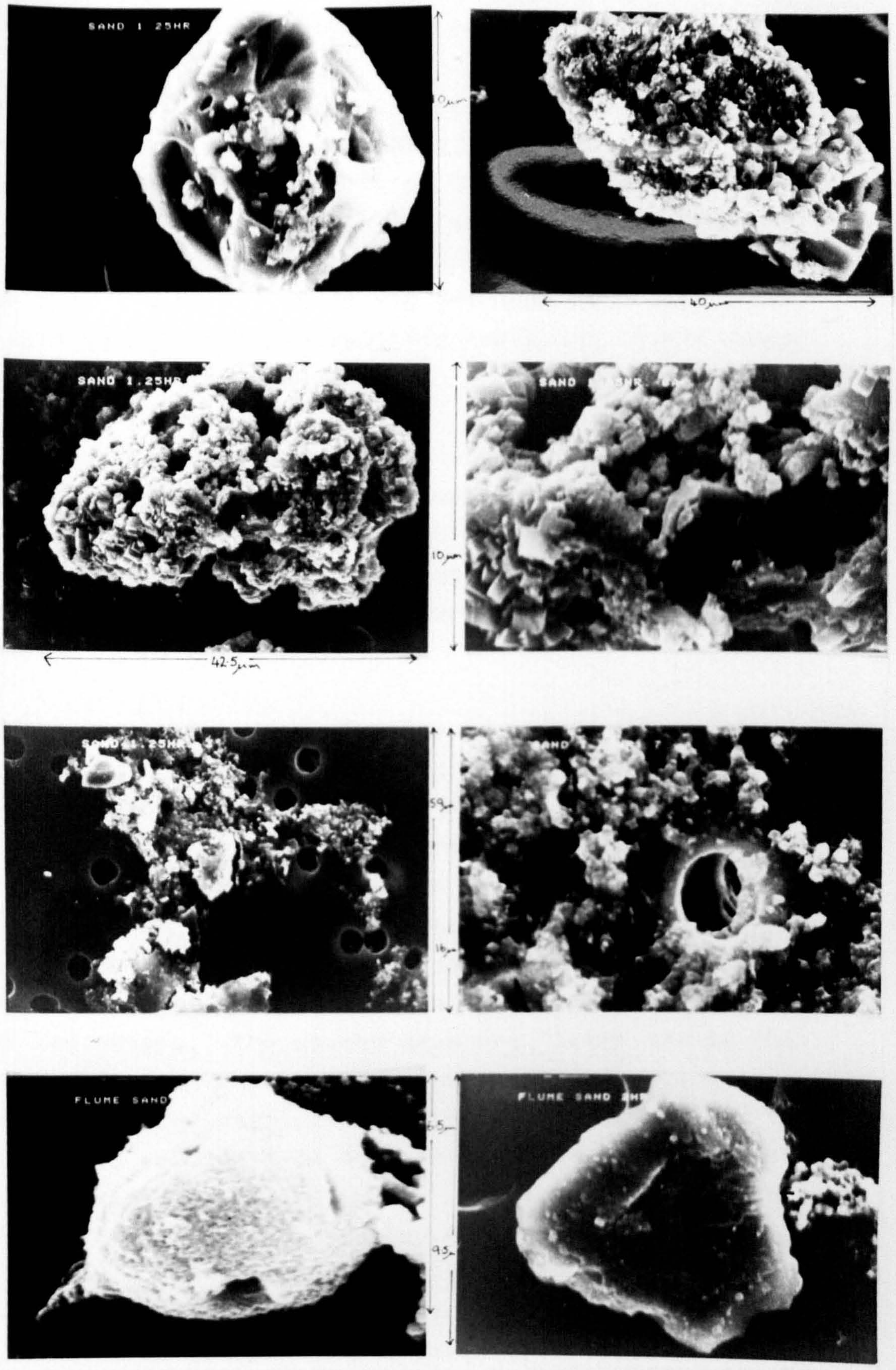
Plate 53 x 1500 Overall view of particles with early precipitates and precipitation and solution on fine fragments.

Plate 54 x 5700 Detail of Plate 53, precipitation and solution on fine fragments.

2 Hours: Development of Precipitation and Aggregation.

Plate 55 x 11500 Rounded grain with a few large abraded cavities and the surface severely affected by solution or precipitation, and attached to edge of small aggregate.

Plate 56 x 8700 Subangular particle, surface affected by abrasion and solution, step features (→), loosely adhering fine particles.


SAND 1 25HR
40μm
SAND 1.25HR
10μm
42.5μm
FLUME SAND
6.5μm
9.5μm
FLUME SAND

available in soluble forms such as opal from, for example, grasses and diatoms (as described in Chapter 3).

At the end of 2 hours the development of precipitation has incorporated most of the particles into aggregates (Plates 55-61). The increased percentage from 40% after 1.15 hours to 78% after 2 hours is shown on Table 9.4. with a corresponding increase in development, particularly of precipitation from 3.0 to 3.4. Table 9.4 shows the increase in precipitation over this period and the resulting reduction in the number of abrasion features observed.

The steady rate of growth of precipitates and aggregates from 1.15 hours to 2 hours continues to 2.45 hours (Plates 62-67). Precipitation development reaches a peak at this time although the percentage of aggregates (Table 9.4.) is artificially masked by the occurrence of some fresh faced sediment in this small sample.

Silica precipitation is continuing to spread after 3.45 hours although its growth is being curtailed (Plates 68-74). The precipitates take two forms. At first the granular form is seen predominantly which appears bright from the effects of charging and thus indicates only a loose attachment to the substrate; it also develops extensively from particle fragments and off extremities of particles. It is probably the early stage of overgrowth development described by Waugh (1970) and others. The second develops later and is that form commonly seen on the stormwater sediment. The precipitate develops from the particle surface and on most of the surfaces. It appears to develop from the particle and may be optically continuous with it (Waugh, 1970). The surface is smooth from the effects of weathering by solution.

By 4.30 hours (Plates 75-81) precipitation has affected, and largely covered 100% of the particles (Table 9.4). From

Plate 57 x 11600 Silica precipitation advancing over irregular particle with fresh-faces (right), most advanced on particle extremeties.

Plate 58 x 3800 Small aggregates forming of particles with precipitates developing and surrounding particles.

Plate 59 x 5700 Precipitation on and around particles which are abraded and support early precipitates.

Plate 60 x 8700 Detail of granular precipitation–solution material.

Plate 61 x 8400 Detail of well-developed precipitate, assumed to be silica.

2.75 Hours: Growth of Precipitates and Aggregates.

Plate 62 x 3800 Subrounded particle with abraded edges and slight surface abrasion and solution, particularly in central cavity.

Plate 63 x 3800 Uniform low relief surface precipitation, more irregular precipitates and solution in central cavity.

Plate 64 x 8700 Silica precipitation growing at edges of irregular angular particle with fresh faces seen from beneath precipitate.

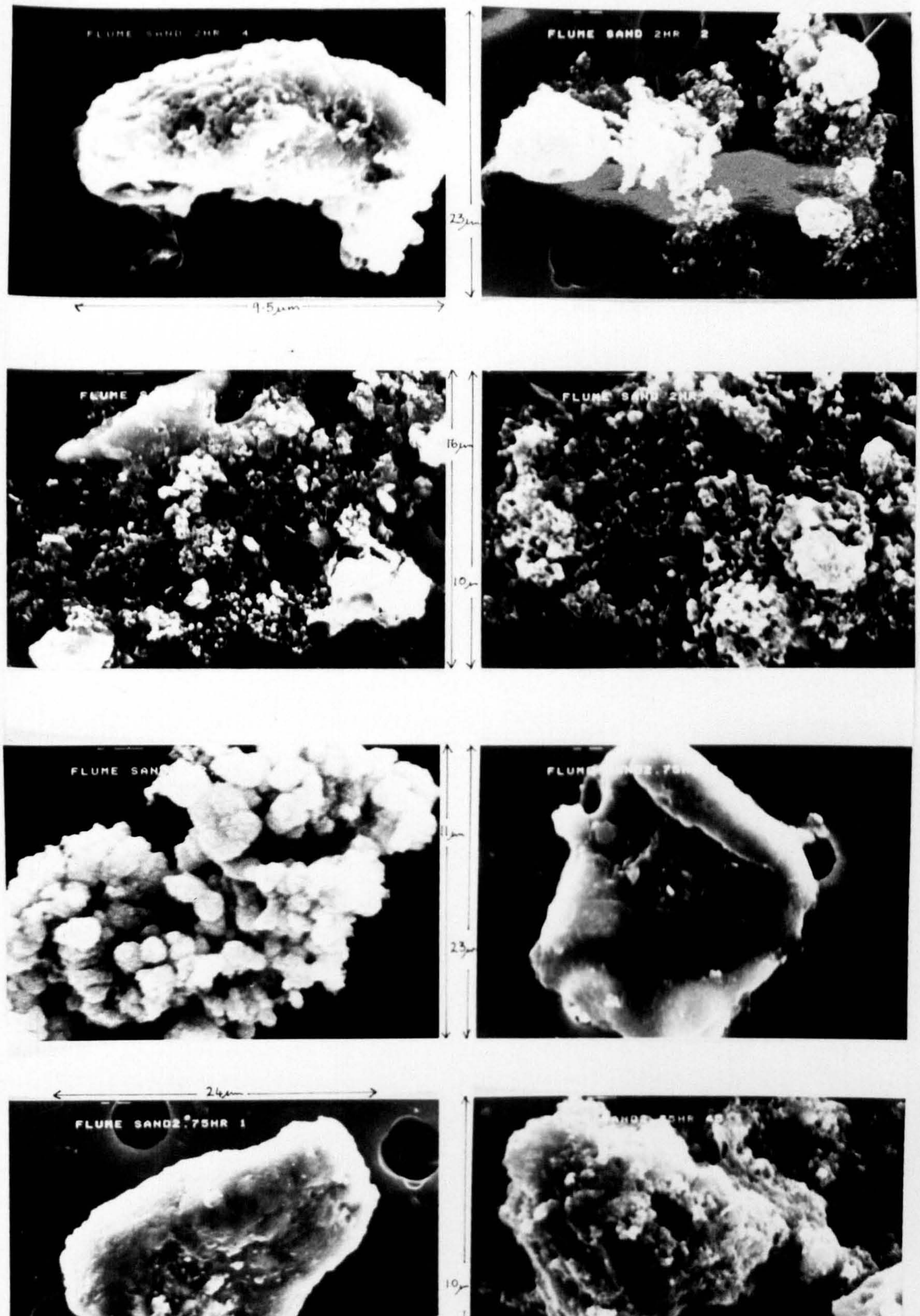

FLUME SAND 2HR 4
FLUME SAND 2HR 2
23µm
9.5µm
16µm
10µm
11µm
23µm
24µm
FLUME SAND2.75HR 1
10µm

Plate 65 x 2600 More advanced silica precipitation and solution concealing the particle surface but not the cavities of upto 3.5μm diameter.

Plate 66 x 1400 Spreading precipitate incorporating fine particles.

Plate 67 x 8700 Detail of square and cubic crystal development with silica precipitation on and around the crystals (side 2μm).

3.75 Hours: Continued Precipitation and Aggregation Development.

Plate 68 x 2600 L.h.s. granular silica growth on and around particle; r.h.s. angular particle with smooth spread of precipitate growing on particle (no charging) (→).

Plate 69 x 5700 Well-developed granular silica precipitation.

Plate 70 x 2600 Aggregate forming of granular silica especially off edges and ridges of particle.

Plate 71 x 8600 Fresh-faced, subangular particle well covered by silica precipitation.

Plate 72 x 3800 Fresh-faced particle with some sharp corners removed by abrasion and impact pits on faces and edges; upper, strongly weathered surface of solution hollows, adhering particles and early precipitation, lower right.

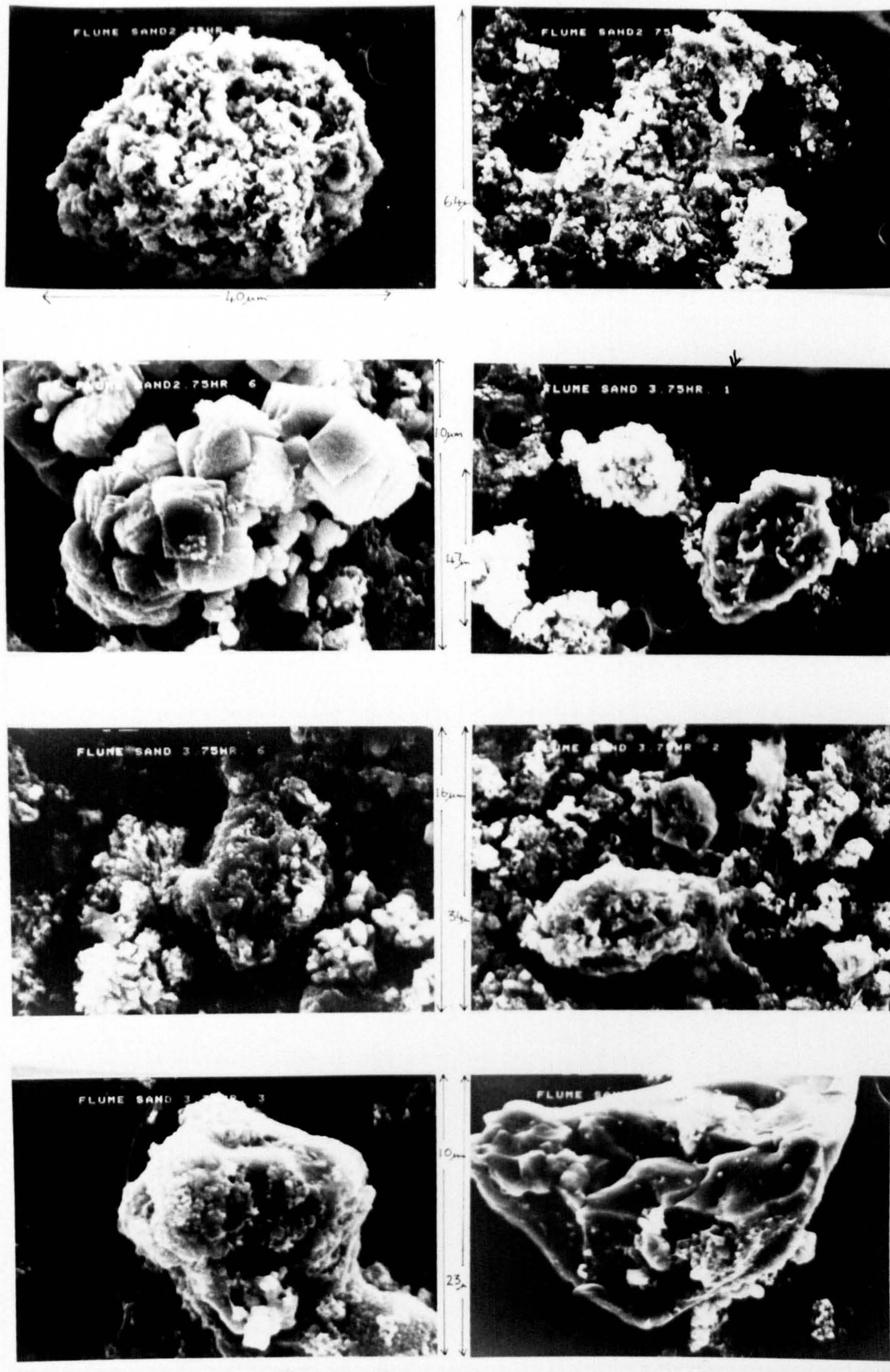

FLUME SAND 3.75HR. 1
FLUME SAND 3.75HR. 6
40µm
64µm
10µm
47µm
16µm
34µm
10µm
23µ

Plate 73 x 11700 Detail of Plate 72, solution hollows (0.05-0.2μm diameter), apparently in a surface layer as shown by abraded lower edge. Surface adhering particles appear to have been plastered on with considerable force.

Plate 74 x 8700 Angular particle with relatively fresh face and surrounding precipitation.

4.5 Hours: Further Development of Precipitates.

Plate 75 x 8800 Convoluted particle of fresh faces and edges with developing precipitates; upper right, less affected by precipitation but exhibiting circular solution hollows.

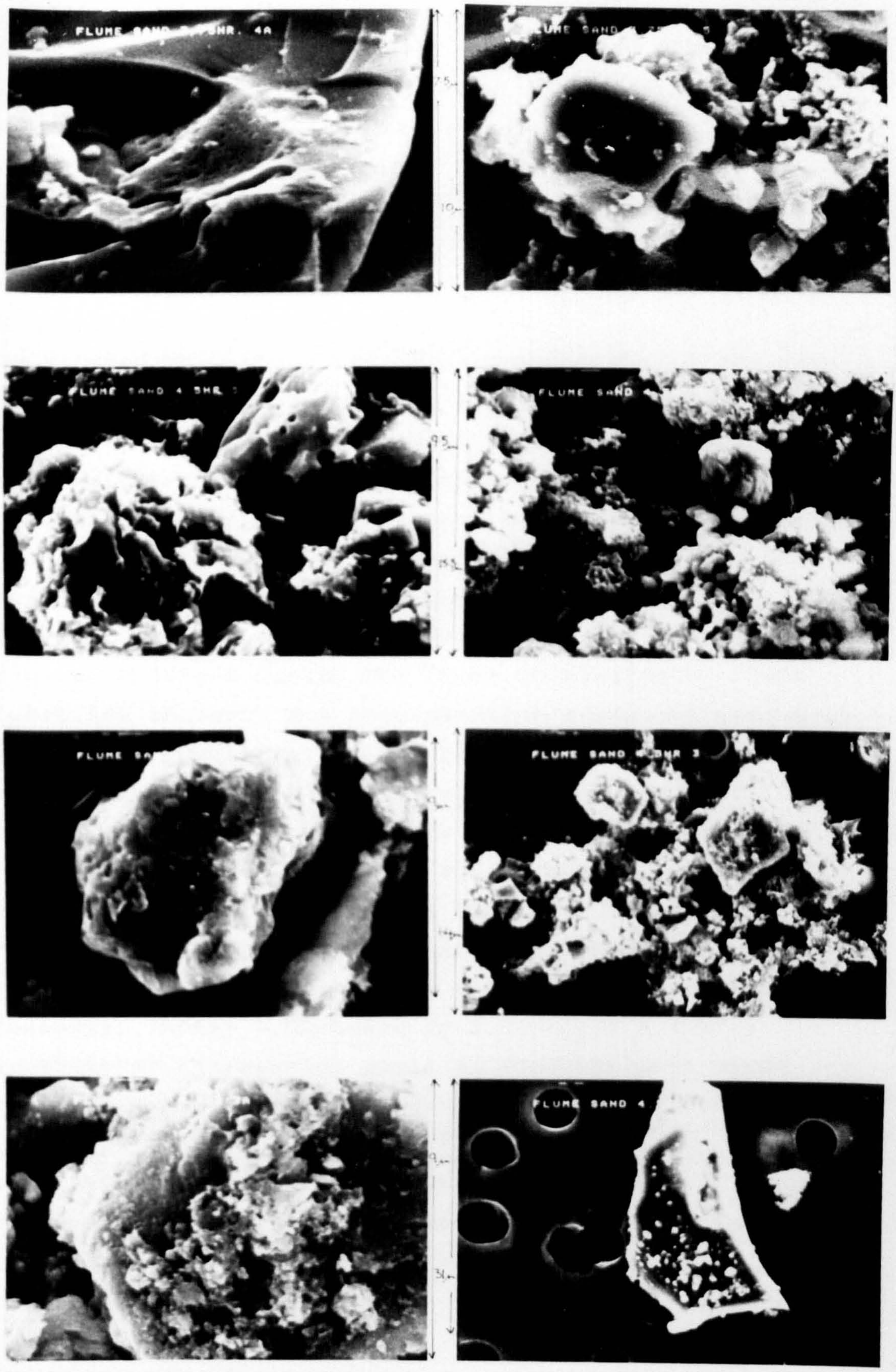
Plate 76 x 5700 Increase and spread of precipitates.

Plate 77 x 8700 Silica precipitation on subangular particle incorporating some fine particle fragments into low relief coating.

Plate 78 x 1400 Eroded and precipitate-covered particles.

Plate 79 x 8700 Detail of precipitation-solution surface and fine granular form of particle incorporating fine fragments.

Plate 80 x 2600 Very angular particle with abraded cavity and loosely adhering fine fragments.


FLUME SAND
FLUME SAND
FLUME SAND 4

this time onwards however, precipitation and aggregate development are limited by abrasion and both are shown to decrease slightly in development between 4.30 hours and 8.00 hours. It is clearly the effects of abrasion acting on the sediment which restricts continued aggregate development. Table 9.4 shows the continuing high rate of abrasion although at this stage it is rounding the particles by breakage rather than increasing their angularity. Rounding is enhanced by the increased activity of solution processes and later, by the additive formation of precipitates.

Having reached this stage in the stormwater system the discharge decreases which encourages aggregate growth. In the flume however the discharge remains constant and abrasive forces remain strong. Without much prolonged flume transport it is difficult to ascertain whether the state of the sediment will remain fairly constant as might be inferred from the results of 4.30 hours to 8.00 hours. An alternative possibility seems to be that after the initial intense abrasion of sediment during the first 30 minutes of flume transport the abrasion and precipitation processes become cyclical. Once precipitation and aggregation have reached a certain stage, after approximately 4.30 hours, further development is actually limited by the lack of free silica available. A period of abrasion would release more silica but in so doing would be abrading the aggregates themselves and reducing their size. In reality these processes are probably not dominant alternately but are both occuring continuously. After 6.00 hours to 8.00 hours a fairly steady state of aggregation could be expected with minor fluctuations periodically. The occurrence of very few types of features reflects the single source of sediment features; particle abrasion is the sole source of silica for the development of these features.

A slight increase in aggregation was seen after 6.00 hours (Plate 82-88) possibly in response to the increase in precipitation beforehand but little further change is seen after 8.00 hours (Plates 89-92).

6 Hours: Predominantly Aggregate Development.

Plate 81 x 11700 Detail of Plate 80, steps on plain surface and conchoidal breaks (l.h.s.of cavity) chipped off by abrasion and thence acting as precipitation nuclei and growth in protected cavity.

Plate 82 x 5700 More substantial aggregate development of precipitate-coated, and remaining fresh, particles.

Plate 83 x 2500 Spreading precipitate incorporating small particles.

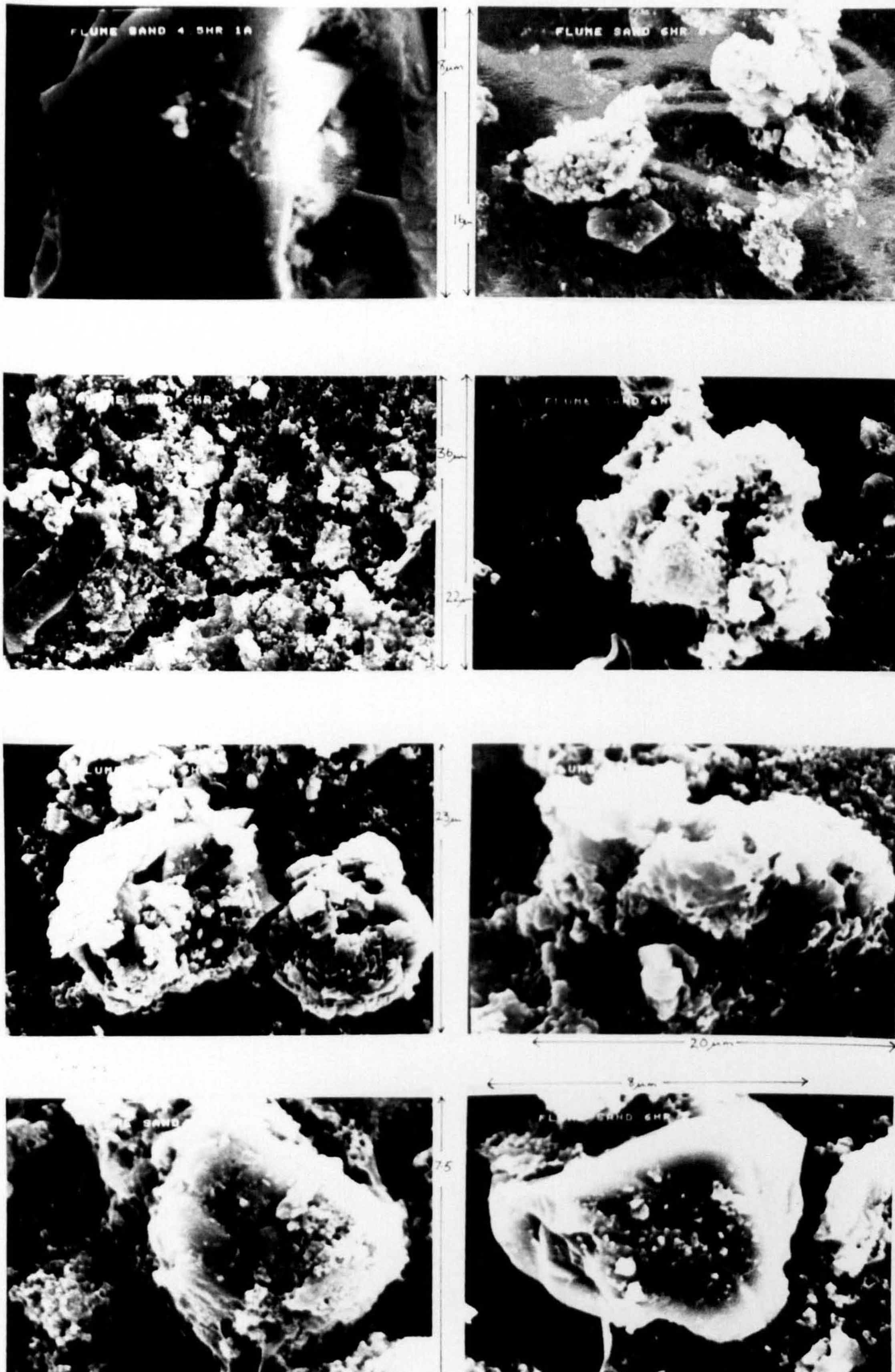
Plate 84 x 4000 Increasing precipitation and aggregation.

Plate 85 x 3800 Silica precipitation on eroded edges of particle which has fresh faces with abraded steps still visible loosely adhering particles and precipitation.

Plate 86 x 5600 Smooth-faced particle moulded by solution with silica precipitation on protected edges; particle aggregated to others.

Plate 87 x 11700 Particle, in aggregate, subrounded, with abraded surface smoothed by solution, precipitation beginning on edge and in hollow.

Plate 88 x 11400 A remnant angular, fresh-faced particle which has largely escaped precipitation but now is being incorporated into aggregate (upper edge); abraded conchoidal steps and 'V' notches.


FLUME SAND 4.5HR 1A
FLUME SAND 6HR
36μm
22μm
23μm
20μm
8μm
7.5
FLUME SAND 6HR

8 Hours: Slowly Increasing Agregation.

Plate 89 x 3800 Small aggregate of subangular particles and small scale precipitation.

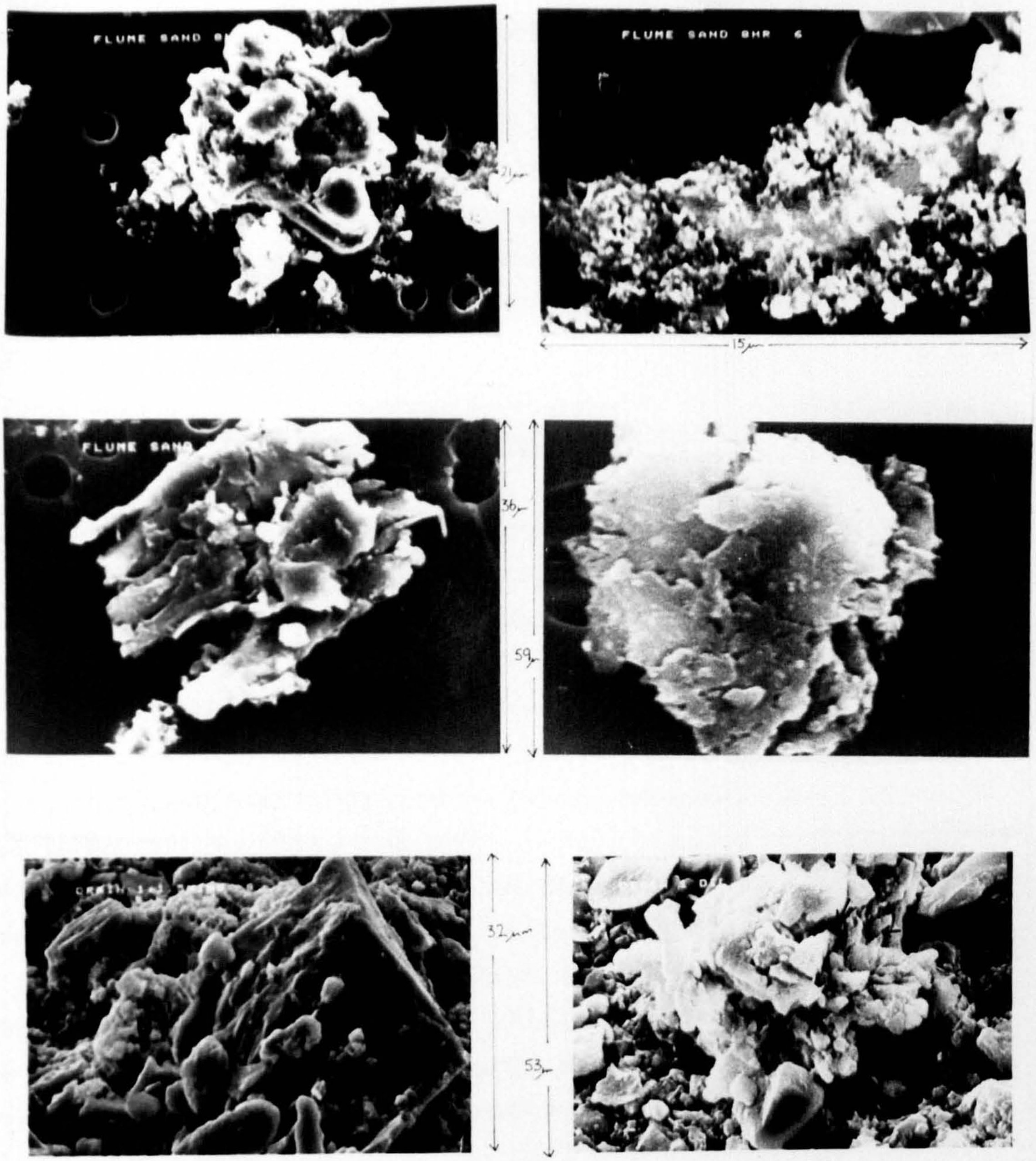
Plate 90 x 8700 Extensive fine granular precipitation.

Plate 91 x 2500 Severely abraded Particle.

Plate 92 x 1500 Severely abraded particle, devoid of precipitation and possibly not quartz.

Plate 93 x 1500 Impact pits, 'V' notches (a), sharp edges and clear faces of abrasion; surface precipitates apparently unaffected by abrasion (b).

Plate 94 x 2600 Frimly cemented aggregate after 10 minutes. abrasion, precipitated silica cement at base of particles (→).


FLUME SAND 8HR 6
FLUME SAND
15μm
36μm
59μm
32μm
53μm

The occurrence in some samples of fresh faced, angular particles is an unexpected anomaly. It is suggested that these particles were lodged somewhere in the system as appears to be the case with fully coated particles occuring after 5 minutes. It is difficult to see where these particles could lie undisturbed in the system or why they should then be re-entrained. A possibility is for particles to be deposited in corners of the receiving tank and later randomly displaced by water or sediment but this is solely conjecture.

9.4. Experimental Ultrasonic Abrasion.

Once more the Fuzzy method of anlysis was adopted for the results of simulated sediment abrasion by the ultrasonic bath. The experiment was to study the effects of abrasion on the sediment but this time the actual stormwater sediment was used. Details of the method are given in Appendix 9. The results of the ultrasonic bath treatment, on a storm sediment sample, for progressively longer time intervals are shown in Table 9.5.

There is a noticeable decrease in the number of aggregates after 5 minutes although they do not completely disintegrate. The aggregates remaining are those in the mature state of being firmly cemented together (Plate 93) while the others were only adhering or in the early stages of cementation. Abrasion features (Plate 93) tend to increase with time, as seen from Table 9.5.

The method of abrasion is severe as shown by the breakdown of the immature aggregates. This is not seen during storm discharges (Chapter 8) but then the discharges during widespread aggregation are well past their peak and declining so a close comparison cannot be made. It is interesting to note the strength of the aggregates which are able to withstand the considerable force of abrasion created in the ultrasonic bath.

TABLE 9.5.

FUZZY ANALYSIS OF SIMULATED ABRASION SAMPLES FROM ULTRASONIC BATH TREATMENT.

Sample Feature	5 mins		10 mins		20 mins	
	μ	%	μ	%	μ	%
A. Aggregates @	1.5	30			3.3	7
B. Si Features	3.4	78*	2.9	92**	2.5	79*
C. Pitting	1.7	37	2.0	17	1.9	54
D. Fresh Face	3.3	56	3.4	83**	2.6	80**
E. Angularity	3.9	67	3.7	50	3.8	81**
F. Steps	1.6	19	1.0	25	2.1	42
G. Impact Pits	2.9	67	2.6	83**	3.2	86**
I. Clays	4.5	15	2.0	8	5.0	6

@ Feature list given in Table 7.3.

μ= Mean Fuzzy value of feature from sample particle.

%= Percentage of particles with feature

71* = Notable values 70-79.

100** = High values 80-100.

9.5. The Usefulness and Limitations of the Results.

The results fulfill the aims of the sediment transport simulation in linking the processes and the features they form. It has been possible to attach time periods to the processes predominating in the flume although they act on the sediment more rapidly there than in the catchment. The limitations of the data and of the inferences made from it must be recognised and mainly derive from the inevitable problems of the small scale of the flume compared with the size of the sewer system (described in Section 9.2.3.)

Evidence for the higher energy of the flume system than the sewer comes from the more rapid rate of abrasion of the particles. It is difficult to compare the flume and drain sediments exactly since the drain sediment surfaces are complex before drain transport and the superimposition of abrasion features may be less obvious than on the flume sediment. The coated sediment was very useful in showing the order of preferential erosion but the large size of both types of trial sediment compared with the storm sediment may or may not produce slight differences in the feature produced.

As described in Section 9.3 above, both the abrasion, and precipitation and solution features formed in the flume appear to be very similar to those on drain sediment.* The abrasion features are clearer and better defined than those on drain sediment which is most likely the result of a single process of transport abrasion, unconfused by the outside influences to which drain sediment is subject. The combined examination of flume - generated surface textures and those from the storms described in Chapter 8 shows that the degree and extent of abrasion features generated in the flume during 30 minutes can scarcely be matched in the sewer system by the maximum rainfall intensities and discharges of Group I storms of 1 to 2 hours duration.

It is significant to note here that the silica precipitation features formed in the flume were in tapwater of approximately neutral pH and thus it appears that pH is not of such importance as has been previously thought.

The flume trials were set up with the aim of studying the processes and features of abrasion. The subsequent precipitation of silica and aggregate formation, so closely emulating the patterns of development found in the storm sewer, was an unexpected bonus. Precipitation did not occur in substantial quantities until after the first 30 minutes of flume transport. Clearly then, it is the abrasion of the quartz in particles which is releasing sufficient silica for precipitation and the ensuing cementation of aggregates. During the early stages of flume precipitation the features produced are very similar to those of drain transport although they form more quickly. Abrasion and precipitation followed by aggregation takes up to 9 hours in Group II storms but the equivalent state is reached in the flume in 4.5 hours. Group II storms are used as a comparison here because they have the combination of high abrasion rates and aggregate formation. From this stage in the flume the continuing high rate of abrasion restricts large scale precipitation and aggregation and erodes aggregates already formed. From this point the flume system no longer simulates the pattern of sediment alteration in the drain. The lower energy conditions of the drain, particularly in the falling stages of discharge, allowed for the greater growth of precipitates. A further sample taken after a stationary period in the flume may have shown further aggregate development. The aggregates in the flume may also be limited to some extent by a lower level of available silica without access to the sources of the catchment; for example, from other minerals and biological sources. It is worth considering however that the pattern of alteration in the flume may well represent a more extensive or higher energy drainage system in which aggregates can form but, for a prolonged period at least, are prevented from developing by severe flow conditions

In conclusion, the time elements of feature development in the catchment remain elusive since the flume trials cannot be used for direct comparison. The problem is one of scale which increases the rates of processes in the flume. However, the simulation is extremely valuable in confirming the link between transport processes and surface textures and the sequence of sediment alteration. The features of abrasion and aggregation can be firmly attributed to the channel hydrological processes and after their elimination further features can be considered largely in terms of sources and land use.

A comparison of the studies of the catchment with the experiments involving both the flume and the ultrasonic bath puts the rate or strength of activity in the drain in context. The ultrasonic bath can easily be seen to be a relatively high energy environment and yet the effects of each system on the sediment places them in increasing order of strength:

(i) Ultrasonic bath - dislodges loose particles, causes minimal abrasion and leaves aggregates intact.

(ii) Sewer system - severe abrasion during most intense storm periods.

(iii) Flume - continuous severe abrasion of particles and limiting aggregate development.

It must be remembered however, that the motion differs in the three situations. During particle transport in the sewer and the flume, particles rotate and exchange energy as they move along the channel in the direction of flow. Protruberances are the most susceptable areas of the particles in such collisions and angular momentum is thus transmitted (Krinsley and Wellendorf, 1980). In the ultrasonic bath particles move in all directions, in straight lines rather than rotating and breakages occur by the cavitation of water between particles; most areas of the particles will be subject to breakage.

It would be of great benefit if other catchment variables could be introduced to complicate the flume system gradually and in a controlled manner. The effects of the variables could then be monitored and a more realistic and useful model would be achieved.

PART IV

CONCLUSIONS

CHAPTER 10

THE SIZE AND SURFACE TEXTURE OF URBAN STORMWATER SEDIMENT.

10.1. Summary of Stormwater Sediment and its Transport History from the Combined Results of Hydrology, Particle Size, and Electron Microscopy Studies.

10.1.1 Group I

The hydrology of storms in Group I is characterised by short duration but high intensity initial rainfall which creates a rapid rise and fall of stormflow and high discharge throughout the storm period (Figure 10.1). The quantity of sediment available depends upon the antecedent conditions but the high capacity of the runoff ensures that particles of all sizes (in the range of 1 to 40μm) are entrained both from the land surface and from within the drain. The sediment is predominantly angular and fresh-faced with abrasion features and the high discharge does not usually allow silica precipitation or aggregation (Figure 10.2) but washes the drain clear of sediment before the discharge falls significantly.

10.1.2. Group II

The storms of Group II have the longest periods of rainfall duration and generate the highest rainfall totals (Figure 10.3). The rainfall intensity and discharge increase gradually to moderately high peak values before gradually falling off. Drain and surface sediment are entrained during almost the entire period of rainfall, and bimodal size distributions are common throughout. At first, the sediment comprises coarse aggregated, drain deposits and finer, individual, fresh faced and abraded surface particles, and gives way to surface fines which predominate until becoming incorporated into newly forming aggregates as the discharge falls and silica

FIGURE 10.1

SUMMARY CHARACTERISTICS OF A TYPICAL STORM OF GROUP I

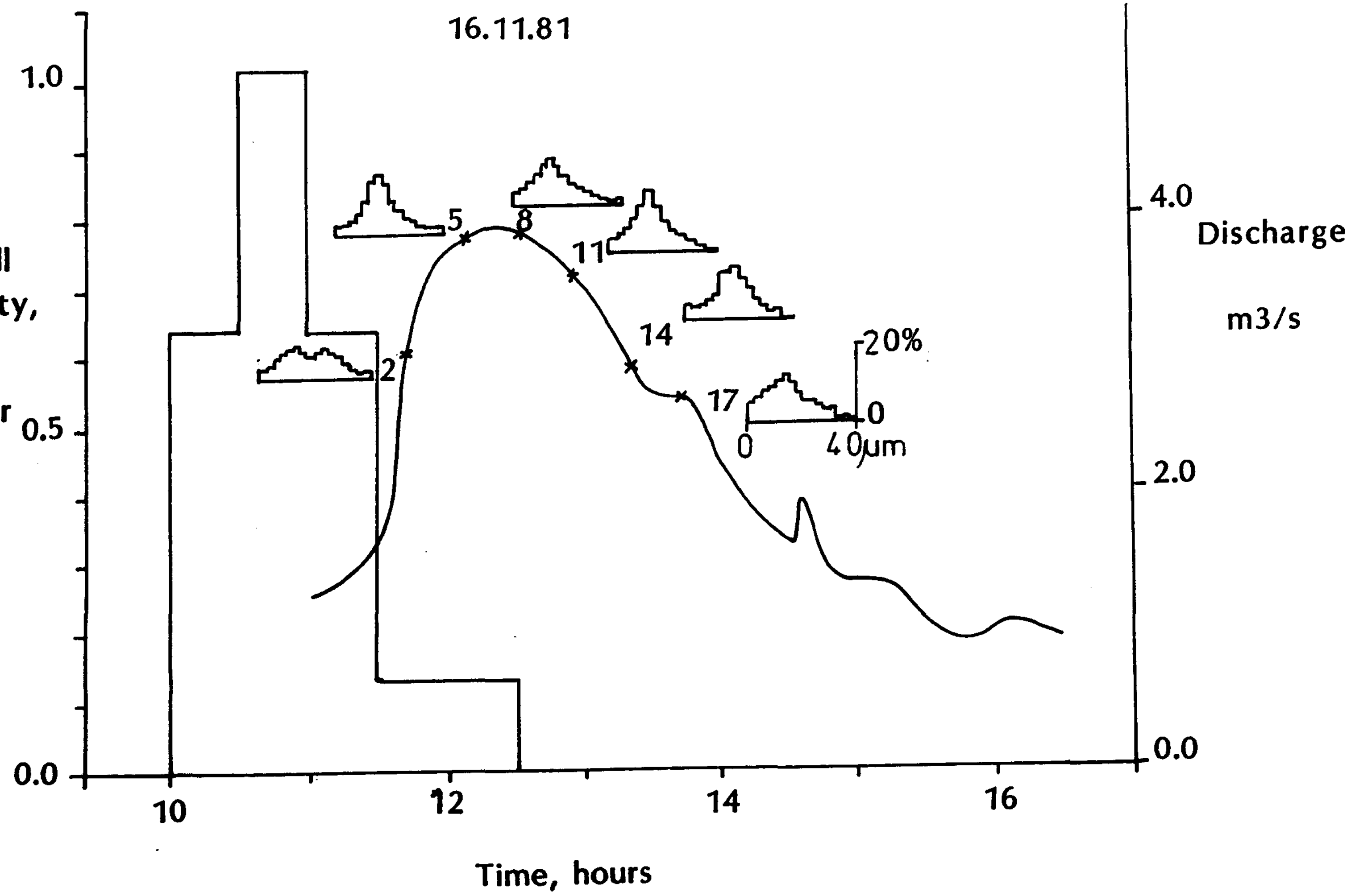


FIGURE 10.2

THE COMBINED RESULTS OF DISCHARGE, PARTICLE SIZE AND SURFACE TEXTURE FOR THE STORM OF 16.11.81

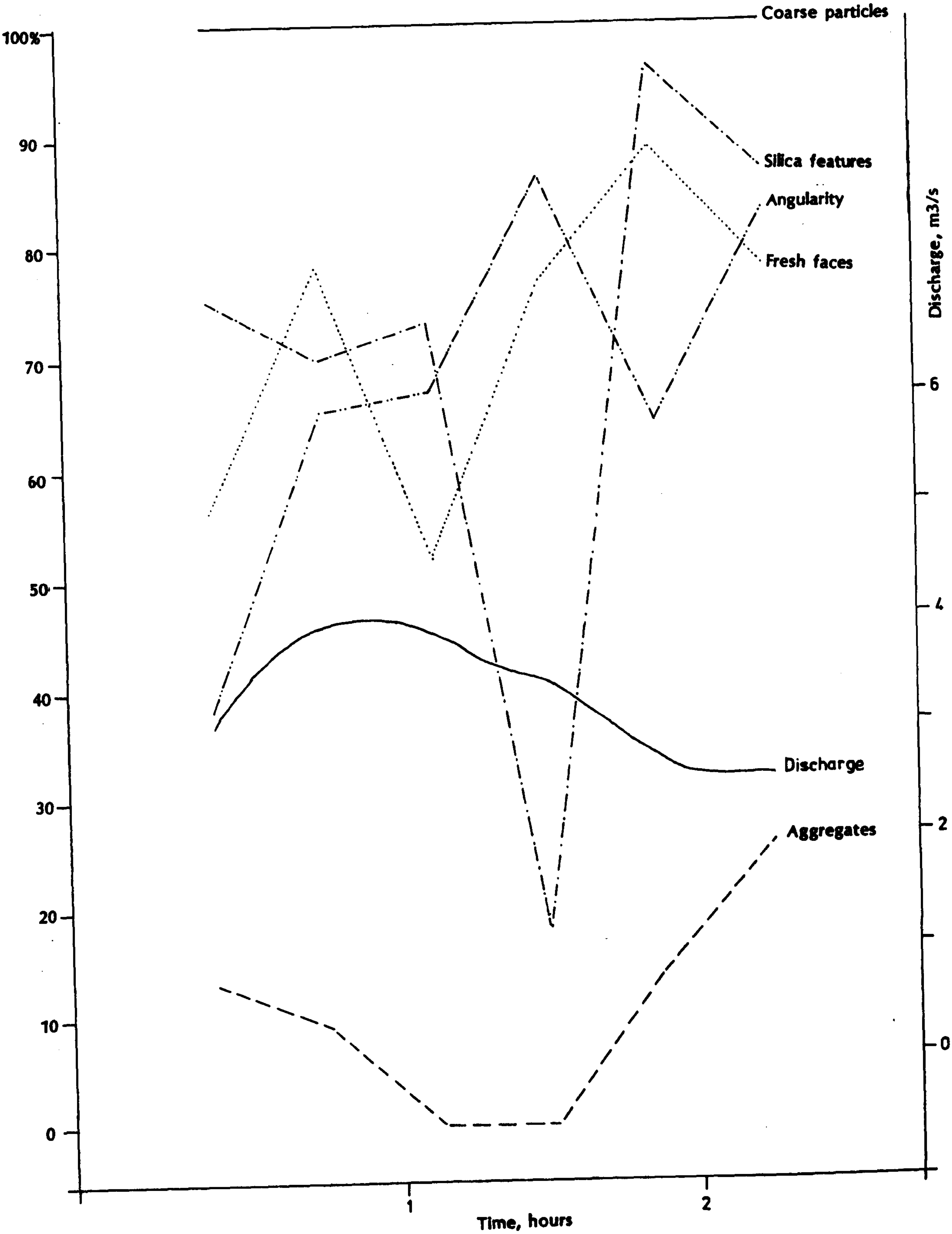
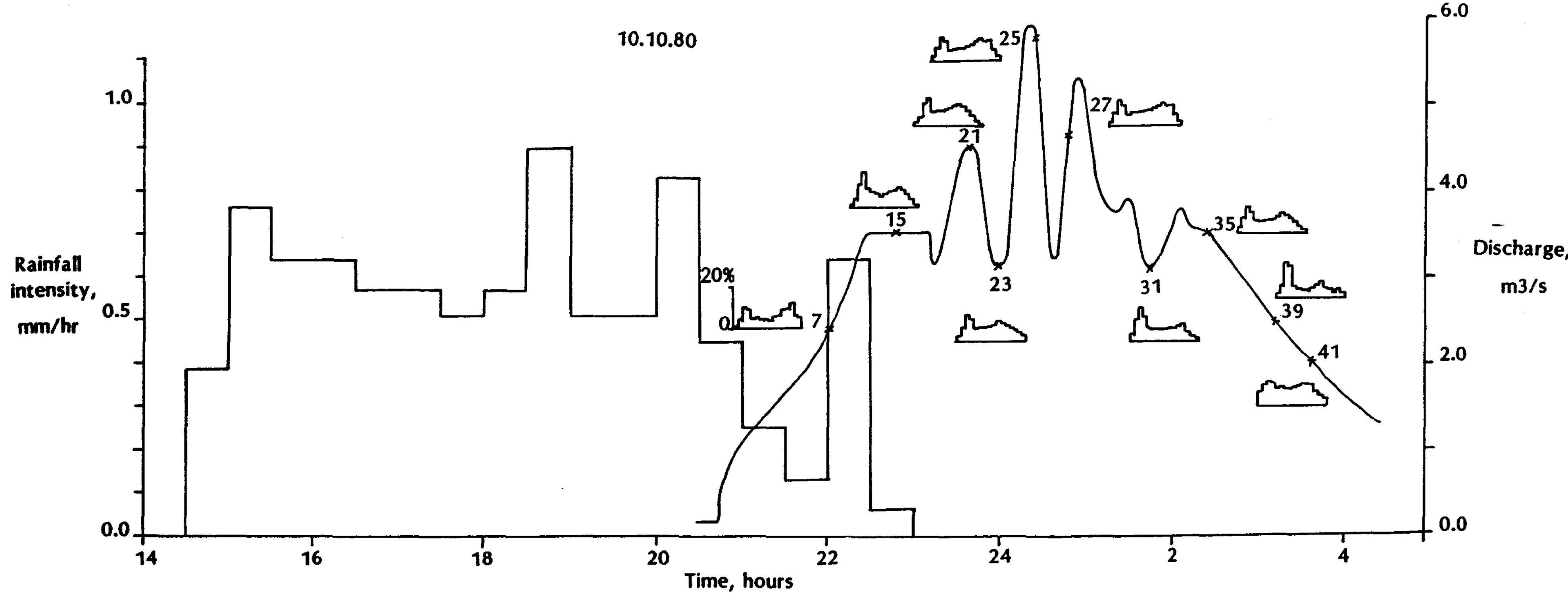


FIGURE 10.3

SUMMARY CHARACTERISTICS OF A TYPICAL STORM OF GROUP II.



precipitation increases (Figure 10.4). The rainfall and discharge may be of sufficiently long duration largely to exhaust the sediment supply and so leave the system clear but usually some coarse, aggregated material is deposited during the falling discharge. Precipitation and aggregation continue to develop incorporating more individual particles, until the flow abates completely.

10.1.3 Group I/II

Storms of mixed grouping result from the occurrence of two storms, of different groups, in rapid succession and have hydrological and sediment characteristics of both storms The point of change of characteristics from one group to the next can be observed from the data and thus such storms exemplify the classification. The initial rainfall of the storm of 17.11.81 (Figure 10.5) fell into the category designated for Group I. The rainfall however, continues for several hours, at a decreased intensity, and generates the discharge regime of Group II storms. The sediment characteristics follow the same pattern, being initially dominated by unimodal particle sizedistributions of fresh-faced, angular and abraded, fine individual particles, and later giving way to bimodal distributions of increasingly silica altered and aggregated particles (Figure 10.6).

10.1.4 Group III

Mid-range values for hydrological, size and surface texture features typify storms of this group (Figure 10.7). The pattern of discharge and sediment alteration follows closely that of Group II storms. As a result of the moderate intensity of the rainfall and the slower build up of the discharge, compared with storms of Groups I and II, surface sediment only reaches the outfall as the discharge attains peak values, and silica precipitation and aggregation occurs to some extent in the early stages of the storms. The constant presence throughout the discharge of transported fine particles and

FIGURE 10.4

THE COMBINED RESULTS OF DISCHARGE, PARTICLE SIZE AND SURFACE TEXTURE FOR THE STORM OF 10.10.80.

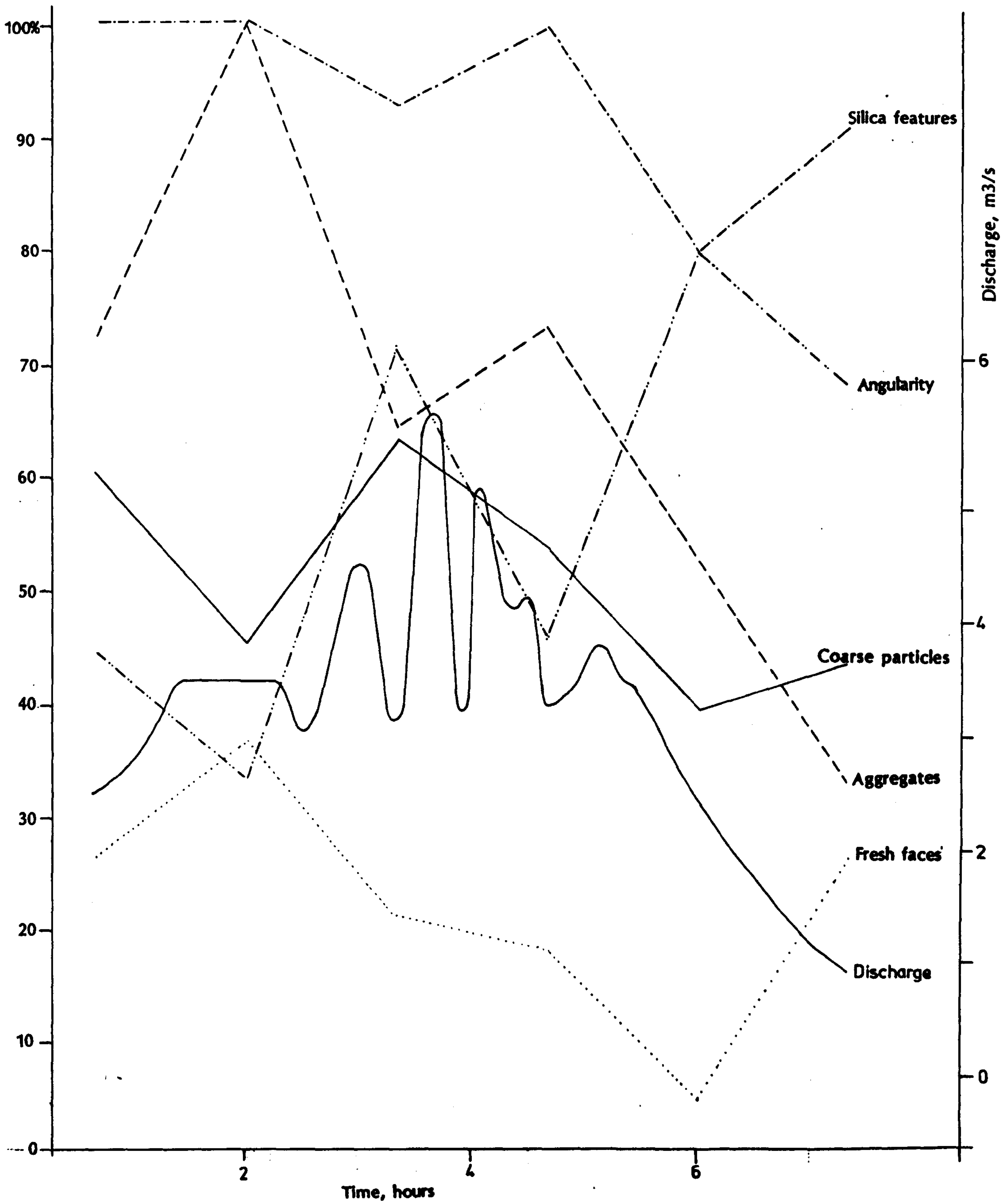


FIGURE 10.5

SUMMARY CHARACTERISTICS OF STORM 17.11.81, OF MIXED GROUPING I/II.

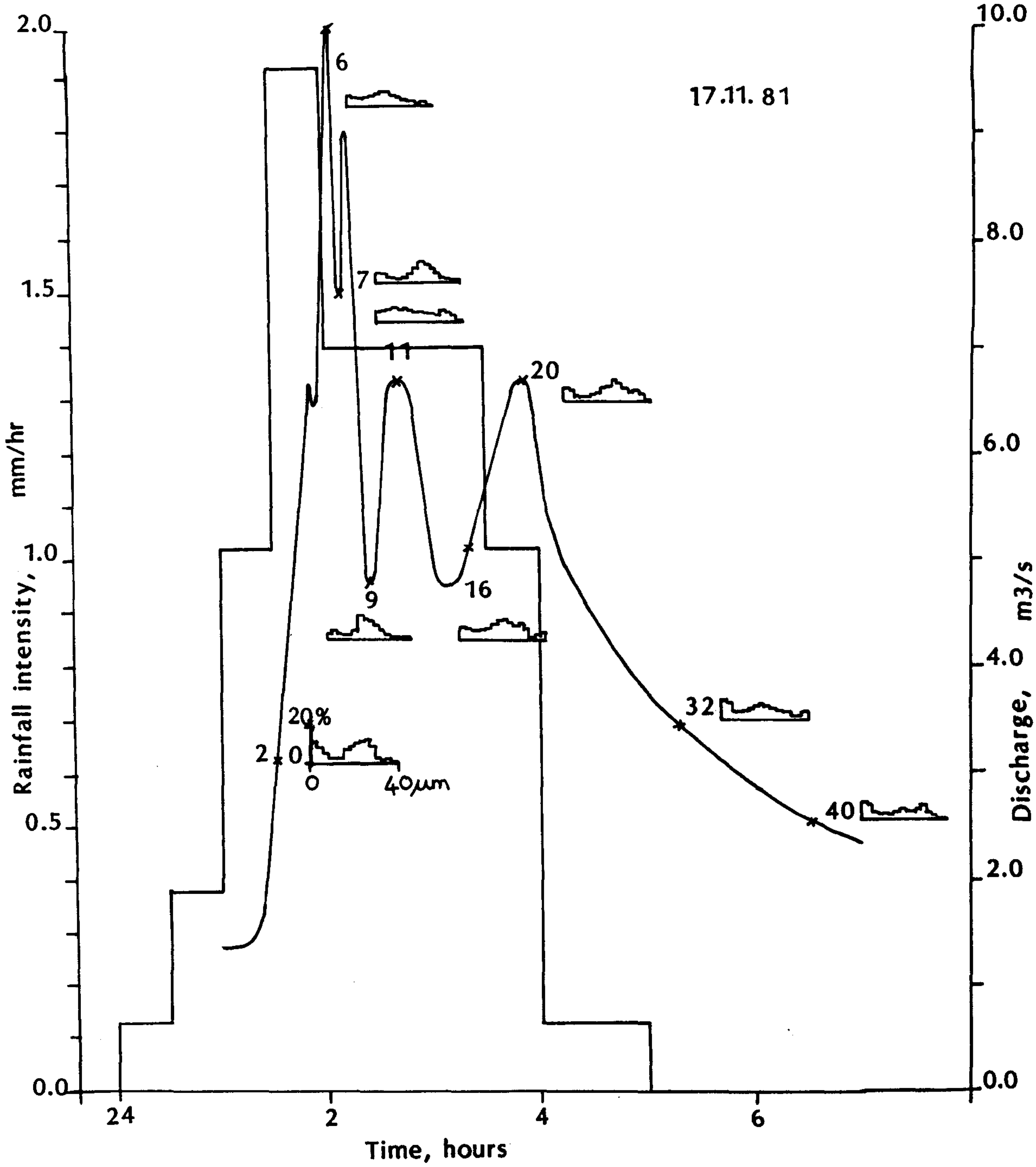


FIGURE 10.6

THI COMBINED RESULTS OF DISCHARGE, PARTICLE SIZE AND SURFACE TEXTURE FOR THE STORM OF 17.11.81.

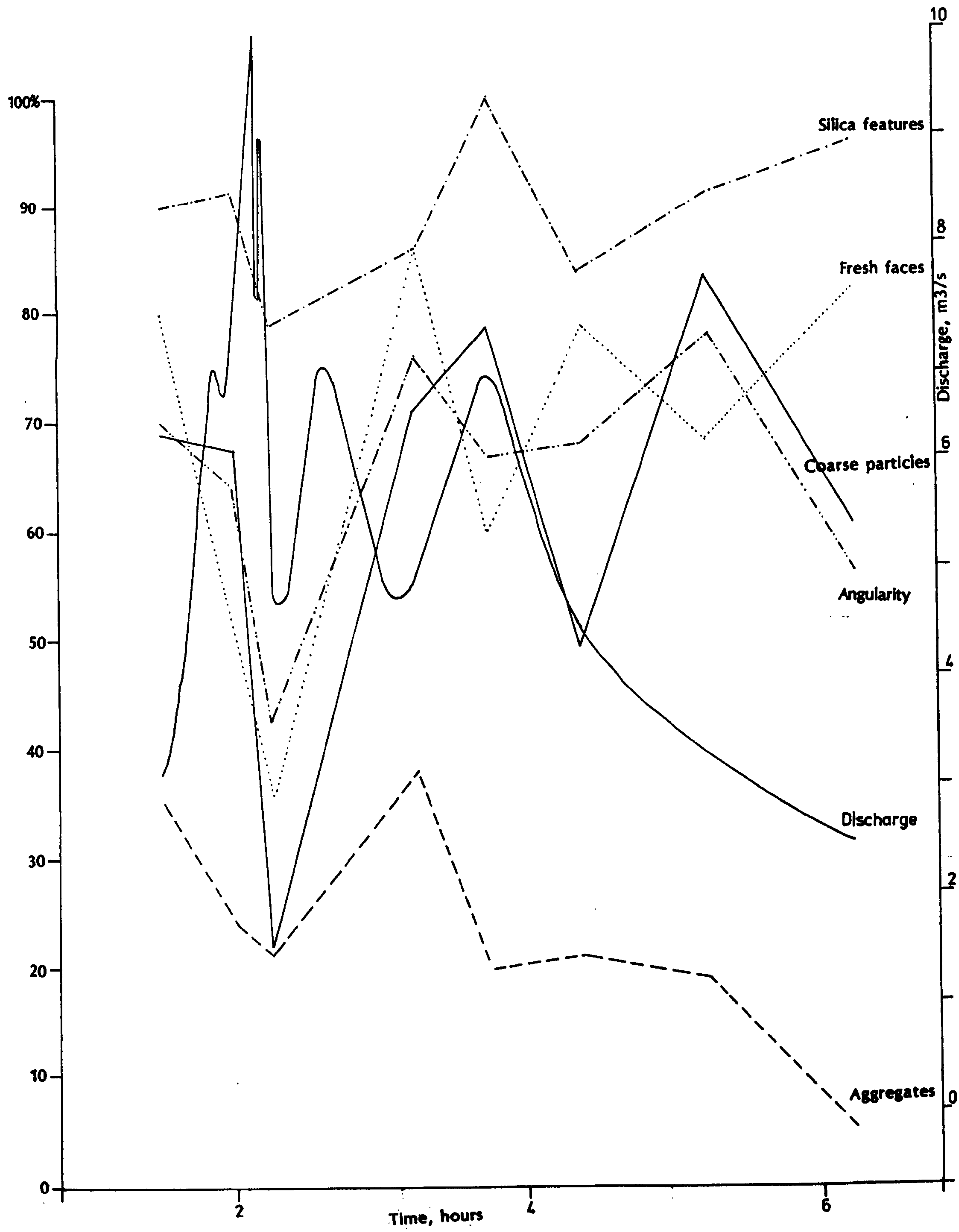
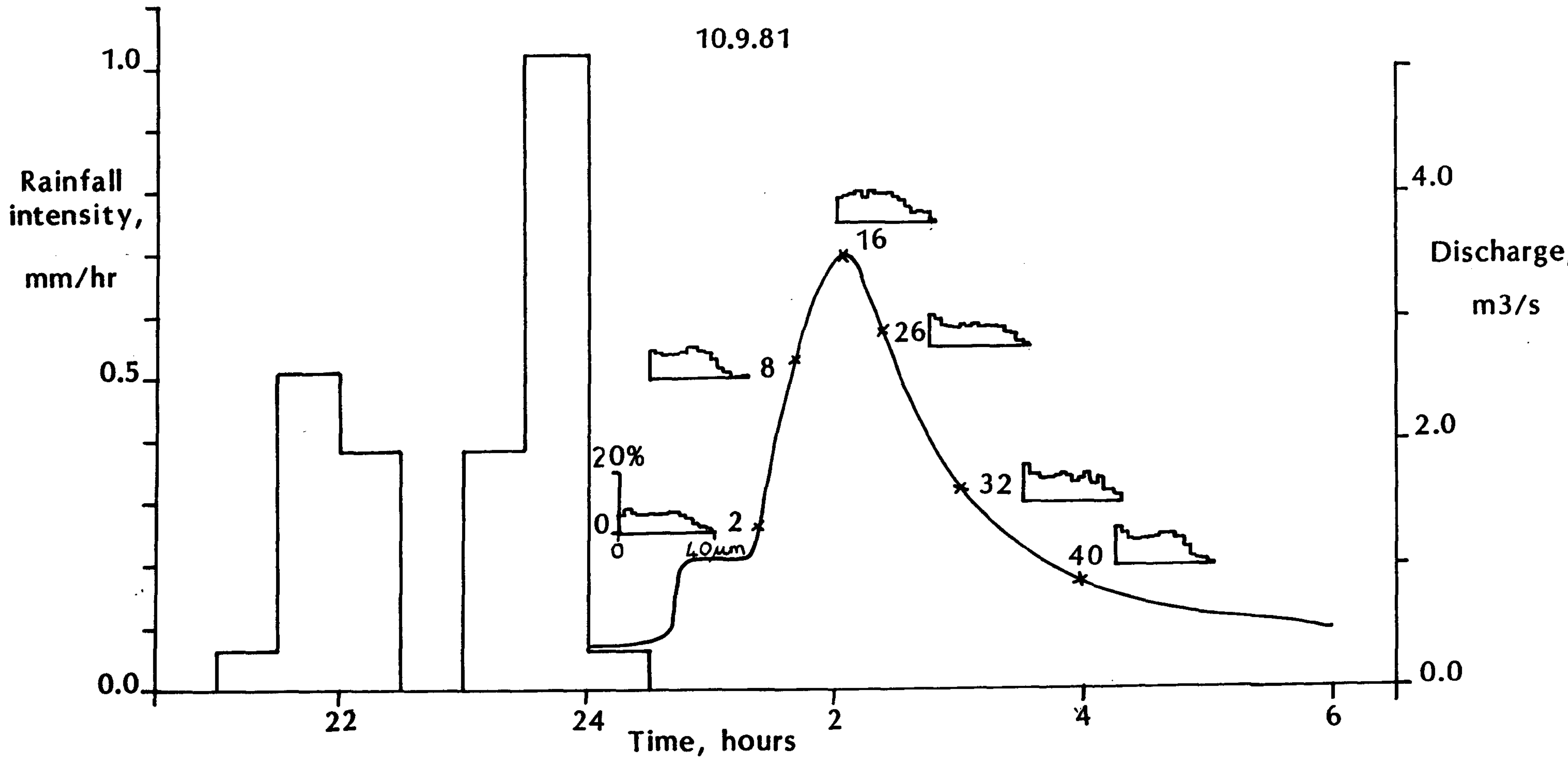


FIGURE 10.7

SUMMARY CHARACTERISTICS OF A TYPICAL STORM OF GROUP III.



the almost continuous forming of aggregates, both early in the storm and during the falling discharge, maintains strongly bimodal sediment size distributions (Figure 10.8).

10.1.5 Group IV

Group IV includes the storms of shortest duration, lowest rainfall totals and intensities and discharge (Figure 10.9) and those which transport the lowest quantities of sediment Minimal abrasion occurs to this sediment but silica precipitation and aggregation is an almost continuous process during these storms. There is a period of wetting of the land surface, depending on the antecedent conditions, before there is sufficient flow for runoff. Precipitation and aggregation occur during these periods of stationary or slow flow. Predominantly the capacity of the discharge is too low to carry any but the finest individual particles but intermittently fluctuations allow the aggregates to be entrained which provides the bimodal sediment size distributions; only the fine particles can be moved any distance (Figure 10.10).

10.2. Conclusions

10.2.1. Suspended Sediment in Urban Runoff.

The sediment in the catchment originates in the largest quantities from the roads; from the erosion by traffic of both the road surface and vehicles. The weathering of building materials produces a substantial proportion of sediment, and soil particles are washed from gardens and open spaces. Airborne particles have their sources both within the catchment and in the surrounding areas but probably mainly from industrial sources rather than deflation.

The size of the sediment once it is suspended in stormflow most commonly ranged from 1 to 40μm. The road surface particles are of quartz and feldspathic mineralogy while the accompanying particles from vehicles include iron, rubber and paint. The most distinctive particles eroded from

FIGURE 10.8

THE COMBINED RESULTS OFDISCHARGE, PARTICLE SIZE AND SURFACE TEXTURE FOR THE STORM OF 14.11.80.

The discharge curve is taken from the storm of 10.9.81, data is unavailable for 14.11.80 but similar rainfall makes the comparison valuable.

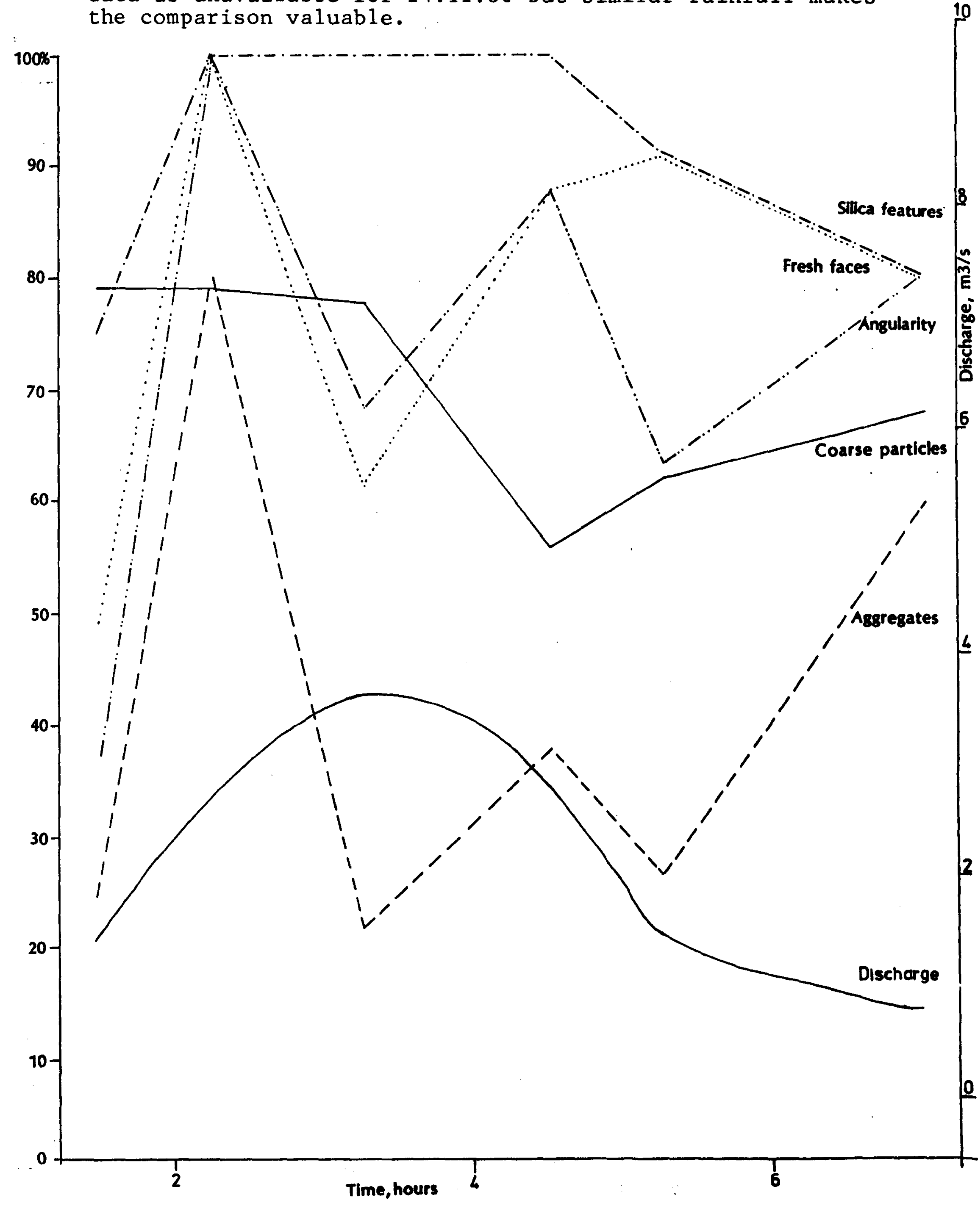


FIGURE 10.9

SUMMARY CHARACTERISTICS OF A TYPICAL STORM OF GROUP IV.

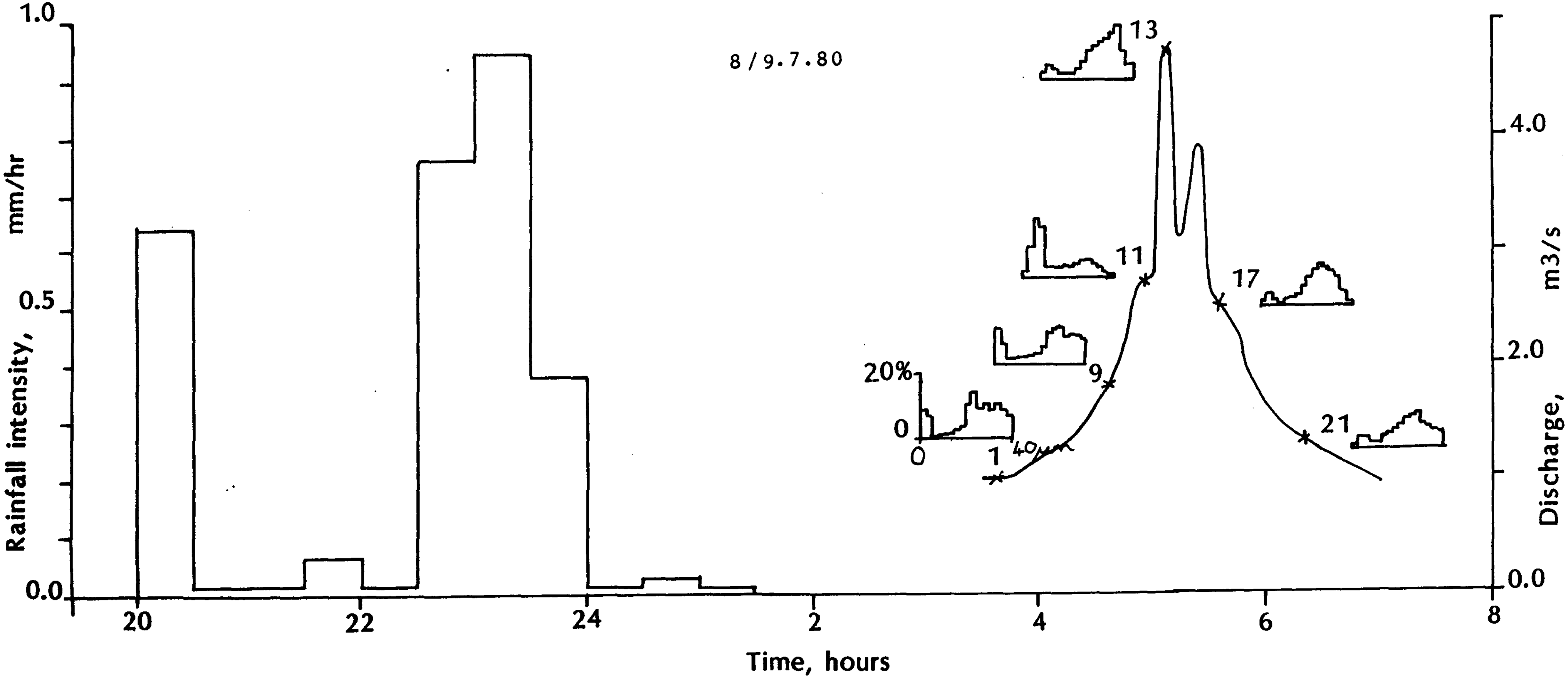
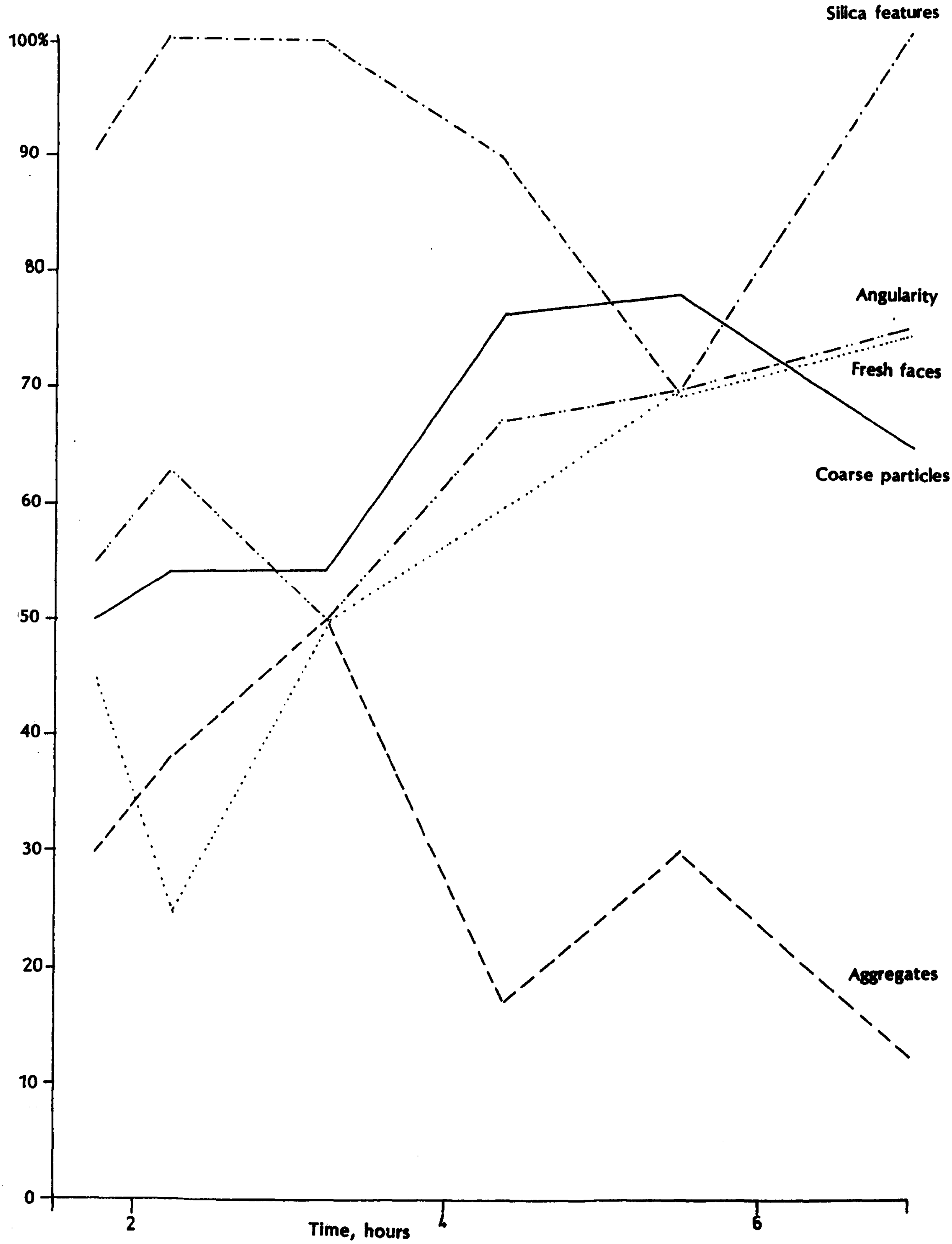


FIGURE 10.10

THE COMBINED RESULTS OF DISCHARGE, PARTICLE SIZE AND SURFACE TEXTURE FOR THE STORM OF 26.11.81.



building materials are the clays from bricks and roof tiles. Soil particles are also predominantly quartz with alumino-silicates, and airborne sediment is characteristically quartzitic, from roads and buildings, and flyash.

The quartz particles from the road surface, apart from being generated in the largest numbers are the most durable, and so account for the vast majority of the sediment sampled at the outfall. The particles were most strongly eroded in areas of heaviest traffic; they are fresh-faced and angular with the well-defined abrasion features. The minority of road sediment from vehicles varies in appearance with its composition but too few particles occurred for the mineralogy and surface texture to be clearly associated with each other. The degree of weathering of particles from building material depends largely on the age of the property. The older brick built housing generates well weathered particles of "crinkly" appearance whereas those of more modern areas are more angular and fresh-faced. Some small variation also occurs due to the slightly different mineralogical composition of some of the newer building materials. Soil particles showed signs of abrasion but are greatly affected by silica precipitation and solution features, from circulating pore waters, which tend to cement the particles into small aggregates. The appearance of the airborne particles falls into two categories; spherical particles of flyash have "upturned-plate" surfaces and the quartzitic fragments are angular with fresh-faces and, occasionally, silica plastering.

10.2.2. Sediment Relationships with Catchment Hydrology.

The storms fall into four main groups based on rainfall and discharge parameters and the characteristics of the sediment collected during these storms are closely associated with the hydrology. Group I is of high initial rainfall intensity for the shortest periods and generates moderately high rainfall totals; the discharge is moderately high and also short-lived. Group II storms are of long duration, high total rainfall and moderately high intensity. The discharge is moderately high and also of long duration. Groups III and IV followed the pattern of Group II but the parameters are of moderate and low values respectively.

The runoff entrains the sediment generated during the antecedent dry period, which collects in the gutters, is washed through road drains into the stormwater sewer and thence, suspended in turbulent flow, is transported to the outfall. During storms of Group I almost all the sediment available is entrained and the land surface is often scoured by the high intensity rainfall. Individual, surface particles therefore predominate in number over any drain aggregates and the sediment is flushed out due to the high discharge. In Group II storms, in contrast, individual surface particles are gradually entrained as the flow builds up. Precipitation occurs during the low flow before particles join the load of drain sediment. Aggregates are removed as the discharge increases and individual particles predominate until aggregation resumes. The sediment is usually removed from the drain due to the prolonged duration of the rainfall and discharge. The sediment loads of Group III storms largely follow the same pattern, as that in Group II, of surface and drain sediment removal but sediment is commonly deposited in the drain with the falling of the discharge. Fine surface particles and aggregates already in the drain, can only be entrained by Group IV storms. Discharge fluctuations occur during stormflow but only in Group IV storms may the discharge fall sufficiently low to affect the sediment and periodically to deposit and re-entrain the larger aggregates of the load.

10.2.3. Sediment Transport Histories.

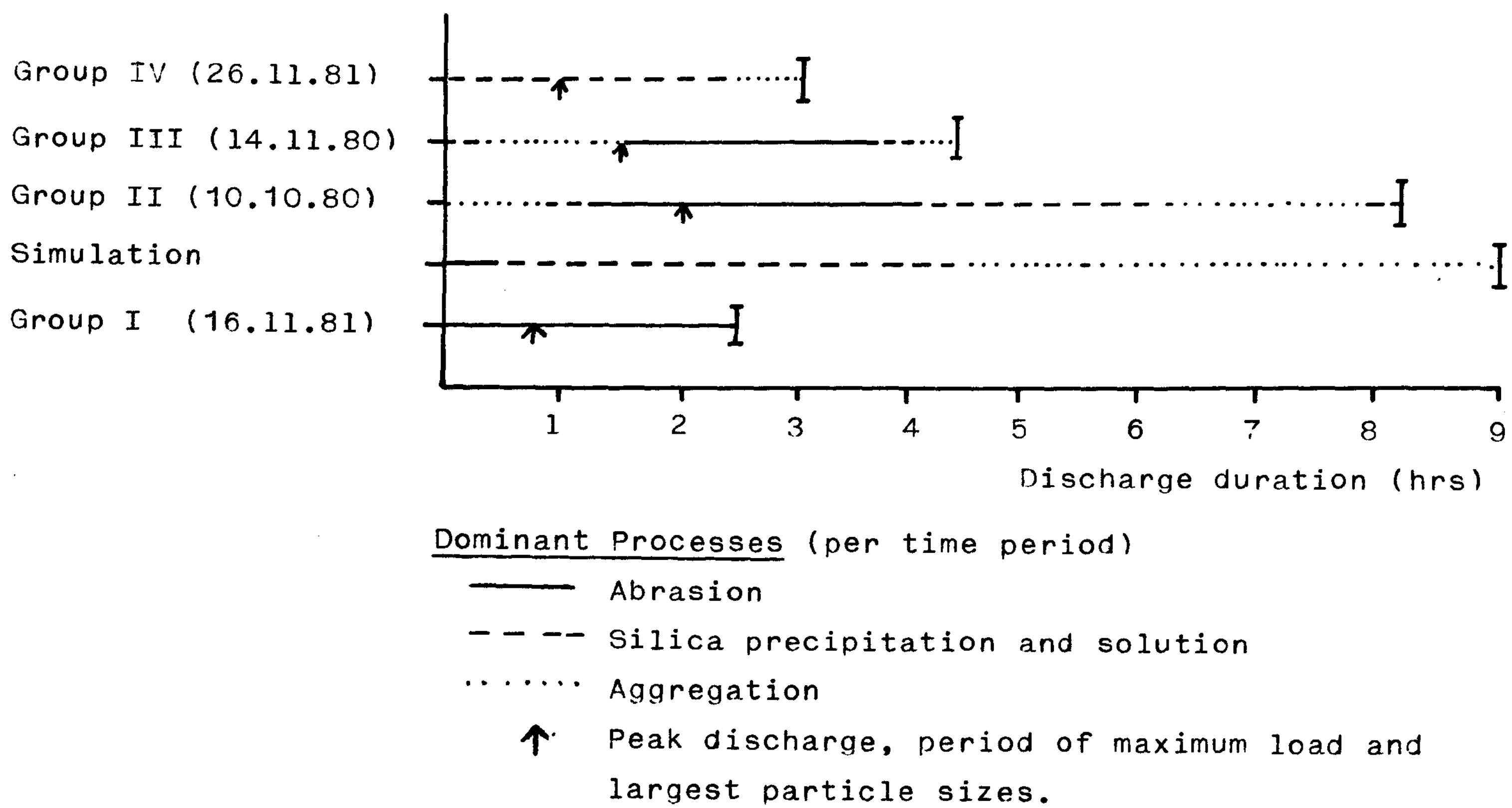
From the source to the outfall the sediment undergoes considerable alteration. After transport across the land surface to the storm sewer, during which abrasion and possible some precipitation occur, the processes of alteration during sewer transport become more vigorous. The degree of alteration varies with the strength and duration of the discharge of the four storm groups but the pattern of progressive alteration remains the same. The highest discharge encourages interparticle, and particle bed abrasion and particle breakage. Breakage most commonly causes angularity and fresh-faces, and abrasion creates impact pits, striations, steps and 'v' notches. Abrasion appears to occur preferentially on particle edges and protruberances and later on faces and in hollows. Solution too erodes and rounds the particle surfaces. As the silica concentration in the water rises, from such sources as the particles themselves, amorphous silica and the decay of plant and animal matter, it is increasingly precipitated onto the particles. At first the silica precipitation is in a fine, granular form which grows and coalesces into globular precipitates. The silica spreads, covering particle surfaces and developing outwards from the particle. In the most extreme cases quartz crystals form but all forms are subject to abrasion by particles and, in particular, by solution which accentuates the rounded appearance of the precipitates. Precipitation continues for as long as the moisture is available and clustered and deposited particles become firmly cemented together, by the precipitate, into aggregates.

The time periods of the different processes remained elusive within the limits of the start of the rainfall and the end of the discharge. In fact, those limits could only be relied upon in instances when the drain was clear of sediment both before and after a storm. The discharge of the runoff and the drainflow could only be measured at the outfall which, combined with the range of particle sizes, prohibits the calculation of surface sediment entrainment values. Further, the time taken to transport sediment from any point along the drain cannot be assumed to be proportional to the distance due to the changing gradient, discharge and sediment load along its length. However some estimation of the period when each process is dominant can be made from the studies of the sediment at known intervals through the storm and with the aid of the flume trials where sediment changes were monitored in a much more controlled environment (Figure 10.11)

The research has shown clearly the close interrelationship between stormwater sediment characteristics and the hydrology. The adaptation of the Fuzzy Method of classification proved to be an accurate and rapid descriptor of distinctions between sediment from different sources, and elucidated stages of progressive alteration occurring along the drain, in particular at the pond, and during storms. It can be seen that features are formed at source or by specific transport mechanisms; some features consistently occur in suites; some features are enlarged, multiplied or replaced, to an extent determined by the distance and duration of transport. The flume-simulation further links processes and features and shows the order of preferential erosion and gives an indication of the time periods of alteration. In the flume it was shown that the abrasion of quartz provides a substantial source of silica for precipitation, while in the sewer there is the added contribution from organic matter. Silica precipitation and cementation of particles forms coarse aggregates which, with fine, individual particles fresh from the surface, create distinctly bimodal size curves. This pattern is only changed by the unimodal distributions of individual particles of all sizes scoured from the surface by severe, high intensity rainfall. This clearer understanding of the nature of the sediment its source, size and progressive alteration during its transport history, will enable implications to be made for more efficient sediment collection and removal and for improved sewer design and operation in urban stormwater systems.

FIGURE 10.11.

A COMPARISON OF PERIODS OF SEDIMENT ALTERATION DURING DISCHARGE.



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APPENDICES

APPENDIX 1

SILICA SOLUBILITY AND PRECIPITATION.

Amorphous silica commonly exists as a colloid or as opaline silica both of which have similar solubilities and dissolve in either fresh or marine waters to levels of 100 to 140ppm at ordinary temperatures (approximately $10^{o}c$) largely as the monomolecularform (H_4 Si O_4). Crystalline forms of silica have lower solubilities; quartz is the lowest at 6 to 14ppm (only affected by pH values of greater than 9, Appendix Figure 1) and thidymite, cristobalite and chalcedony are only slightly higher.(Krauskopf, 1959; Okamota, Okura and Goto, 1957; Berner, 1971) Opaline silica is commonly the predecessor of quartz silica and forms from the skeletal components of planktonic organisms (for example, diatoms) and can also form as an inorganic precipitate. Opaline silica comprises submicroscopic crystallites of disordered crystobalite and inter-crystalline water. The quartz silica can form as euhedral overgrowths on detrital grains, as microcrystalline cement in sandstones and shales and as chert (fibrous crystals of chalcedony) (Berner, 1971).

The weathering of silicate minerals provides a source of silicon. The rate of weathering depends on the number and accessibility of the cations which are removed first: calcium magnesium, iron, sodium and potassium. With the decreasing concentration of these cations per unit volume, the silicates are;ortho-, ino-, phyllo- and tekto silicates. Weathering causes almost complete structural breakdown ofortho- and inosilicates, more superficial alteration of phyllosilicates and considerable structural weakening in tektosilicates such as feldspars which contain these cations.

The breakdown of organic matter causes acidification which leads to the increased production of hydrogen ions and increased rates of hydrolysis. High alkalinity then results from the hydrolysis, immediately around the crystal faces, which causes the release of bases, for example sodium, potassium, calcium and magnesium. This increases the solubility of silicon and aluminium.

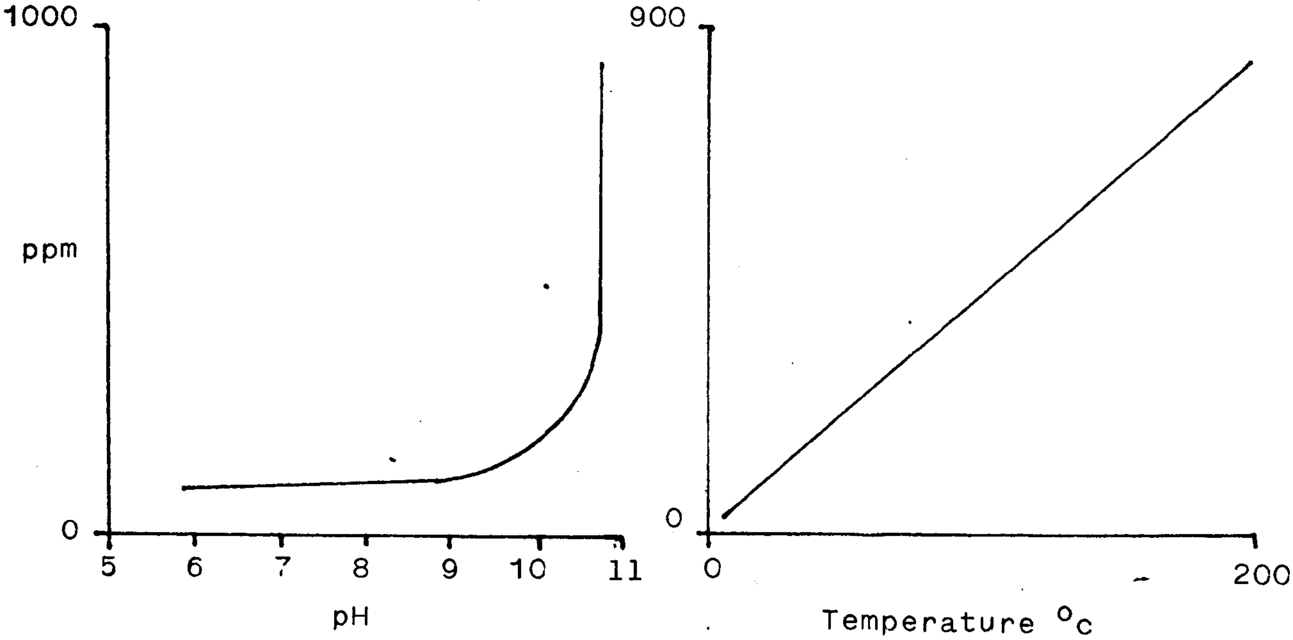
At pH values of less than 9, commonly found in fresh and sea waters, dissolved silica occurs in solution as monomeric silicic acid at a concentration of approximately 35ppm. This is considerably undersaturated compared with possible levels of 100 to 140ppm at 10^{o}c and pH6 but is of similar ionic strengths to fresh and sea waters. The value may be higher with more freshly soluble opal present or lower with quartz or chalcedony (Krauskopf, 1959; Berner, 1971).

The solubility of amorphous silica in the form of synthetic silica gel, colloid and silica glass has been measured at various temperatures and pH values (Kranskopf, 1956). Under ordinary conditions (10^{o}c and pH6, Appendix Figure 1), silica exists in a state of stable equilibrium and is extremely slow to precipitate, possibly taking several weeks. Evaporation, cooling or neutralisation increases the concentration of silica and from a supersaturated solution a colloidal solution forms. Precipitation however appears unlikely especially at pH values of less than 4. However, precipitated silica is found in water courses and forms rapidly (eight hours or less) in the presence of abundant electrolyte as in sea water (pH 7.5 to 8.3) and in the storm sewer (pH 8.3).

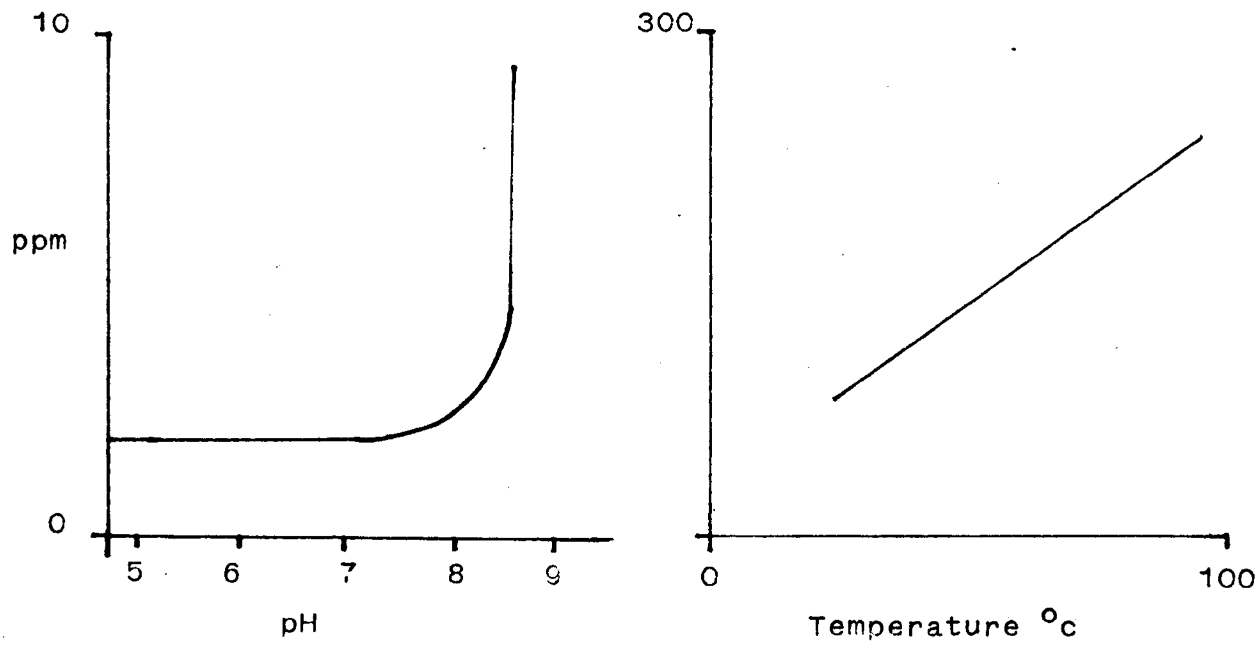
Aluminium plays an important role in silica precipitation. It is released from crystal surfaces of alumino-silicate minerals at the same time as silica and, although in smaller quantities (1 AL : 45 SiO_2), is sufficient to cause precipitation of most of the silica once it has moved away from the area of high pH at the crystal surface. The cations silicon and aluminium are immobile and only move over short distances as colloidal entities. Whereas small amounts of silicon exist as H_4SiO_4 in solution and can move great distances.

APPENDIX FIGURE 1

a. SOLUBILITY OF AMORPHOUS SILICA.



b. QUARTZ SOLUBILITY.



SILICA IN CONCRETE

Some forms of silica used in concrete may, under some circumstances be reactive and cause decay. The reactive forms of silica include microcrystalline quartz and forms whose crystal structures are less stable, for example, cristobalite, chalcedony, tridymite, opal, chert and flint. Caustic alkalis, for example, sodium and potassium hydroxides present in the pore fluid, are taken into solution by water and react slowly with silica particles to form an alkali-silicate gel. The gel is hygroscopic and expands to cause cracking of the concrete (Symposium, Reykjavik, 1975). The proportion of silica is crucial to the reaction and the process does not occur if that proportion is reduced or exceeded. The process is therefore very rare and few cases have been reported in Britain. This is particularly so as the effects are only traced when the reaction occurs near the surface of the concrete. Where this happens the effects of cracking are similar to, and may occur in conjunction with, cracking caused by sulphate attack or freezing and thawing. Although the cracking appears to be rare in Britain, the way in which silica may come out of solution might be more common.

APPENDIX 2

SIGNIFICANCE TESTS OF HYDROLOGICAL PARAMETERS AT 95% LEVEL.

	n	μ	σ_{n-1}
Rainfall Total			
Group: I	6	6.98	4.15
II	7	8.17	2.90
III	5	5.05	1.15
IV	5	2.18	1.54
Rainfall Intensity			
Group: I	5	1.66	0.58
II	7	0.62	0.19
III	5	0.50	0.08
IV	5	0.24	0.26
Storm Duration			
Group: I	6	2.17	0.75
II	6	6.07	1.64
III	5	3.50	1.28
IV	5	2.00	1.17
Peak Discharge			
Group: I	5	12.54	12.35
II	6	13.70	6.52
III	3	5.08	1.38
IV	2	4.60	4.1
Time to Peak Discharge			
Group: I	5	0.75	0.18
II	6	2.24	0.95
III	3	1.54	0.26
IV	2	1.07	0.45
Lag Time			
Group: I	5	1.65	1.37
II	6	4.63	2.59
III	3	4.83	3.74
IV	2	3.25	3.54

APPENDIX 3

THE STABILITY OF STORMWATER SEDIMENT DURING STORAGE.

Introduction.

Some alteration of the sediment was observed during periods of delay between the collection and analysis of samples; there was considerable growth of algae which incorporated the particles into flocs. The sample bottles were necessarily stationary during this period but it was observed that the process was increased rapidly in conditions of light (sunlight or artificial) and warmth (room temperature); within one day the sediment was largely incorporated into these flocs. The process was slowed to two days when storage occurred in the dark and for longer in the dark when refrigerated. However the introduction of sodium azide in the concentration of approximately 2.5g per 500ml sample destroyed the algae before growth and to some extent allowed deflocculation after algal growth.

Two hypotheses were formulated as to what was the natural state of the sediment in stormwater and what change might take place as a result of the sampling methods. Firstly, it was hypothesised that the sediment occurred as individual particles within the stormflow and formed into flocs and aggregates during the static period and in the confined space of the sample bottles. It was thought that the plastic material of the bottles and tubing, and cohesive forces in the narrow-bore tubes may have had some contributary effect. If this was the case then dispersion treatment, as advocated by authors on sample preparation for electronic counters (Chapter 3) and in particular the ultra-sonic bath, would separate the particles and return the sediment to its natural state. The second hypothesis supposed that the sediment occurred as aggregates in the natural state and that the dispersion treatment would largely break these down.

Results

Sample treatment was designed to determine the most acceptable hypothesis and is shown diagramatically in Appendix Figure 3. The samples were further examined under the microscope. The results showed that the truth of the hypotheses lay in a combination of the two. Under the microscope it could be seen that the sediment occurred predominantly as aggregates at the coarse end of the size range (3 to 40μm) with loosely adhering, fine individual particles, and a very much smaller proportion of separate particles of various sizes but predominantly in the fine range (1 to 3μm).

After repeated size analyses for four similar samples the average values for the percentage of fine particles were calculated and are shown in Appendix Table 3. The considerable increase in fine particles with the introduction of the samples into the dark indicated a release of algal-held particles. Thereafter the changes are slight although at room temperature there is a decreasing trend in the percentage of fine particles after 27 hours and a final levelling off indicated the cessation of algal activity. At room temperature, after the stabilizing period of approximately 27 hours, the percentage of fine particles increases which demonstrates the activity of the dispersion technique after the algae has died. Up until that time it appears that algal activity partly compensates the effects of dispersion. At low temperatures in the dark there is no evidence of algal activity although the dispersion releases fine particles held on the aggregates.

In conclusion, it has been shown that samples stored at room temperature developed algal growth which incorporated sediment into large, sinuous flocs. Within one or two days the flocs could be fairly successfully dispersed in the ultrasonic bath but after a longer period this became impractical. From the shift in the particle size distribution towards the fine sizes, it can be seen that there is a positive correlation between the length of the dispersion treatment up to 10 minutes and the number of fine individual particles in the sample. The loosely adhering particles have then been removed from the aggregates which thereafter remain stable.

With the addition of sodium azide the problems of flocculation caused by algal growth are greatly reduced. The conditions of storage are far less important once the algaehave been destroyed. Storage in conditions of low temperatures and without light do however help to maintain the samples in their most natural form.

APPENDIX FIGURE 3.a.

THE DESIGN OF SAMPLE TREATMENTS IN STORAGE EXPERIMENTS

Hand sample
taken as the absolute natural state.

Samples kept
at room temperature
in the dark

A
No
dispersion
treatment

B
Samples in
dispersant and
subjected to
ultrasonic bath
treatment before
each analysis

Samples kept in
cold and dark

C
No
dispersion
treatment

D
As B

5 - day period,
twice daily particle
size analysis.

APPENDIX TABLE 3

THE INCREASE IN THE MEAN NUMBER OF FINE PARTICLES WITH STORAGE TIME.

TIME (HOURS)

Sample	0	4.75	23.50	27.0	48.25	51.0	71.25
A 1	7.8*	7.9	8.1	10.9	9.1	9.6	9.6
2	7.9*	9.2	10.5	10.6	9.7	9.6	10.6
3	8.0*	10.2	10.4	10.3	10.5	10.1	10.8
4	6.0*	9.9	10.8	10.4	10.1		10.8
B 1		10.6	6.9**	7.7	10.2	10.6	11.0
2		11.5	7.9**	11.2	10.2	10.6	11.4
3		10.4	7.4**	11.8	9.9	10.6	10.8
4		11.0	8.3**	11.5	9.9		10.7
C 1				10.4	11.0		10.4
2				9.8	10.9		10.3
3				10.5	10.7		10.0
4				9.9	10.1		9.8
D 1				10.5	10.2		10.8
2				11.0	10.0		11.5
3				11.0	10.5		10.5
4				10.4	10.0		11.0

Mean number of fine particles; % results of 4 repeated runs per sample are shown.

* Initial sample straight from storm drain and kept in motion

** Low results probably due to low concentration sample

APPENDIX 4

SOME DETAILS OF FUZZY THEORY.

In an attempt to quantify grain surface textures observed with the Scanning Electron Microscope, values are allotted to the features according to their degree and coverage on the particle. Using a set with a scale of 1 to 5 the features are judged as poorly -,weakly -,moderately -,well-,and very well-developed. These descriptive terms are called "linguistic variables". The value allotted also takes into account the percentage-area of the particle covered by the feature on the approximate scale 1, 25, 50, 75, 100%. The absence of a feature is not registered or can be considered as having the value 0; six categories have been most commonly chosen for this type of analysis (for example, Krumbein, 1938).

The features are analysed and classed by visual inspection. There is a lack of sharp division, or fuzziness between grades. The values allotted to variables have no greater numerical precision than their names (linguistic variables); they are ordinal data and therefore only non - parametric statistics can be used in their examination (Whalley, in Press).

The degree of membership of a group is often given a value between 0 and 1 where 0 denotes "not a member" and 1 denotes "is a member" and values of partial membership fall between the two. The degree of membership can be plotted as a curve against the value given to a variable and functions can be generated (Beddow, Philip and Nasta, 1980; Herman, 1982) by the use of, for example, "old" = U^2 as in Appendix Figure 4a from Zadeh (1975) where;

u = grade of membership
0 = is not a member
1 = is a member.

In this example size is plotted to give a membership function which could have direct measurements but this is time consuming and would not really be the case with 'roundness' or "age of people" for example the set of terms of a linguistic variable, V is V (T). The syntax gives rise to the structure of well-formed sentences in T(V). The term of T(V) from Appendix Figure 4a would be: T (age) = very young + young + not young + old + very old; further terms could be added as needed to describe the group. The terms must be defined by number and are ordered (Whalley, in Press).

Generalised membership functions illustrating the terms "generality", "ambiguity" and "vagueness" are shown in Appendix Figure 4b adapted from Beddow, Philip and Nasta, 1980. Membership functions on a scale of 0 to 1 for roundness and angularity are shown on Appendix Figure 4c. If angularity is defined as:

$$u\ (\text{angular}) = \frac{u\ \text{angular}\ (v)}{v}$$

$$u\ (\text{not angular}) = \frac{1 - u\ \text{angular}\ (v)}{v}$$

$$u\ (\text{round}) = \frac{u\ \text{angular}\ (1 - v)}{v}$$

and if values can be given to u then:

$$\text{angular} = \frac{0}{a} + \frac{0}{b} + \frac{0}{c} + \frac{0}{d} + \frac{0}{e} + \frac{0}{f} + \frac{0.3}{g} + \frac{0.5}{h} + \frac{0.7}{i} + \frac{0.9}{j} + \frac{1}{k}$$

$$\text{not angular} = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \frac{1}{d} + \frac{1}{e} + \frac{1}{f} + \frac{0.7}{g} + \frac{0.5}{h} + \frac{0.3}{i} + \frac{0.1}{j} + \frac{0}{k}$$

$$\text{round} = \frac{1}{a} + \frac{0.9}{b} + \frac{0.7}{c} + \frac{0.5}{d} + \frac{0.3}{e} + \frac{0}{f} + \frac{0}{g} + \frac{0}{h} + \frac{0}{i} + \frac{0}{j} + \frac{0}{k}$$

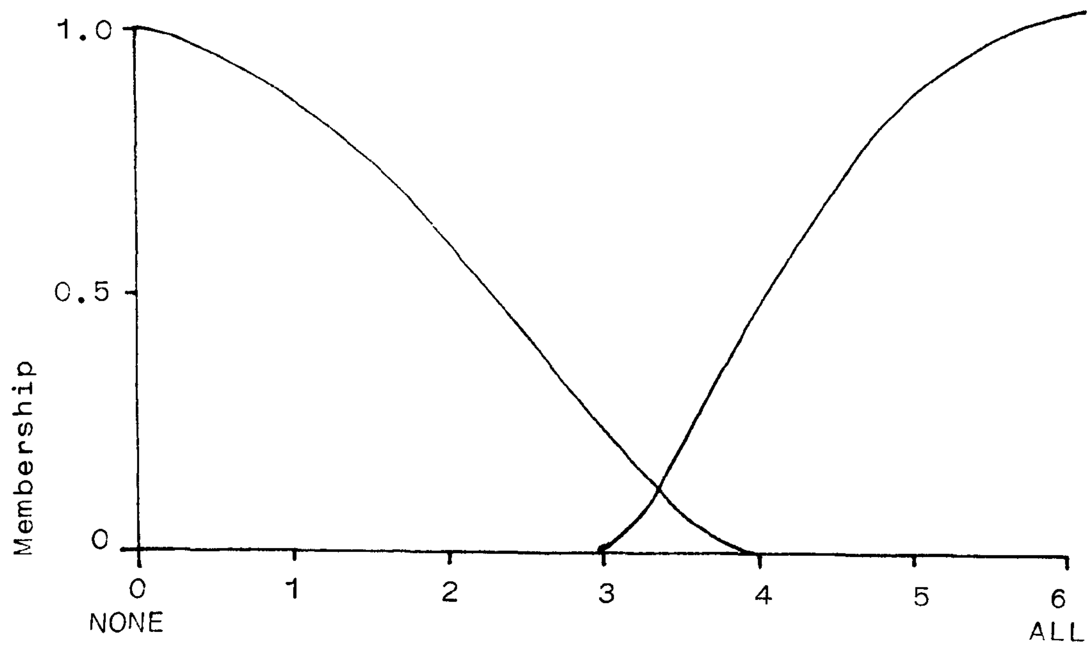
Values of 'u' are for discrete categories (a to k) measured equally for 'roundness' and 'angularity'. Once a term (such as angular is defined and its value (u) at any category determined then it is possible to separate the u's of each term on a bivariate diagram for many data points (Whalley, in Press). There are fuzzy clustering techniques available for this (Bezdek, 1974).

The process of grain texture identification by fuzzy analysis is rapid and features can then be attributed to the source or point in a storm from which they were sampled.

APPENDIX FIGURE 4a

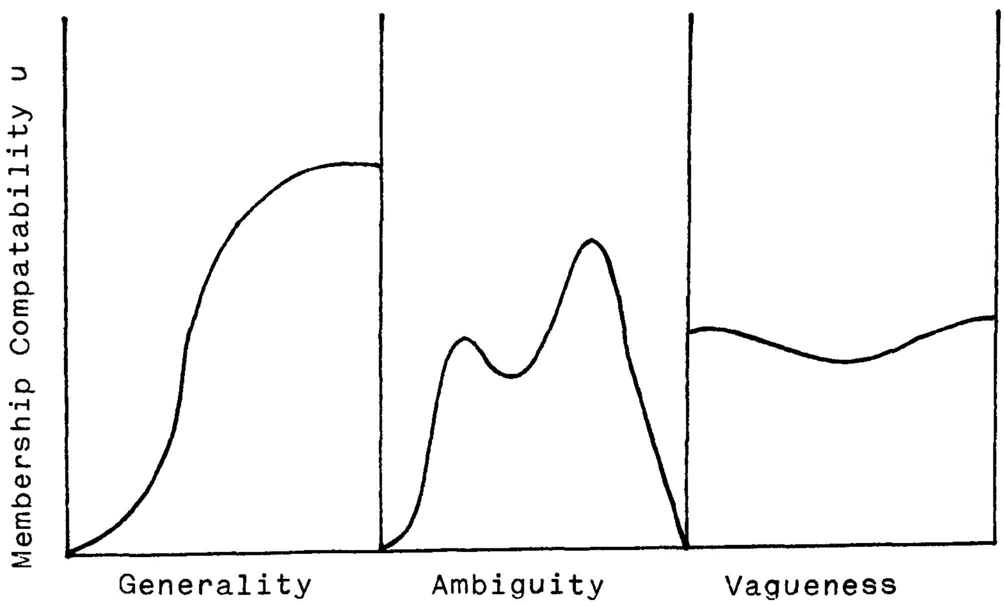
MEMBERSHIP FUNCTION OF THE LINGUISTIC FUNCTION 'AGE'.

(After Zadeh, 1975)



APPENDIX FIGURE 4b

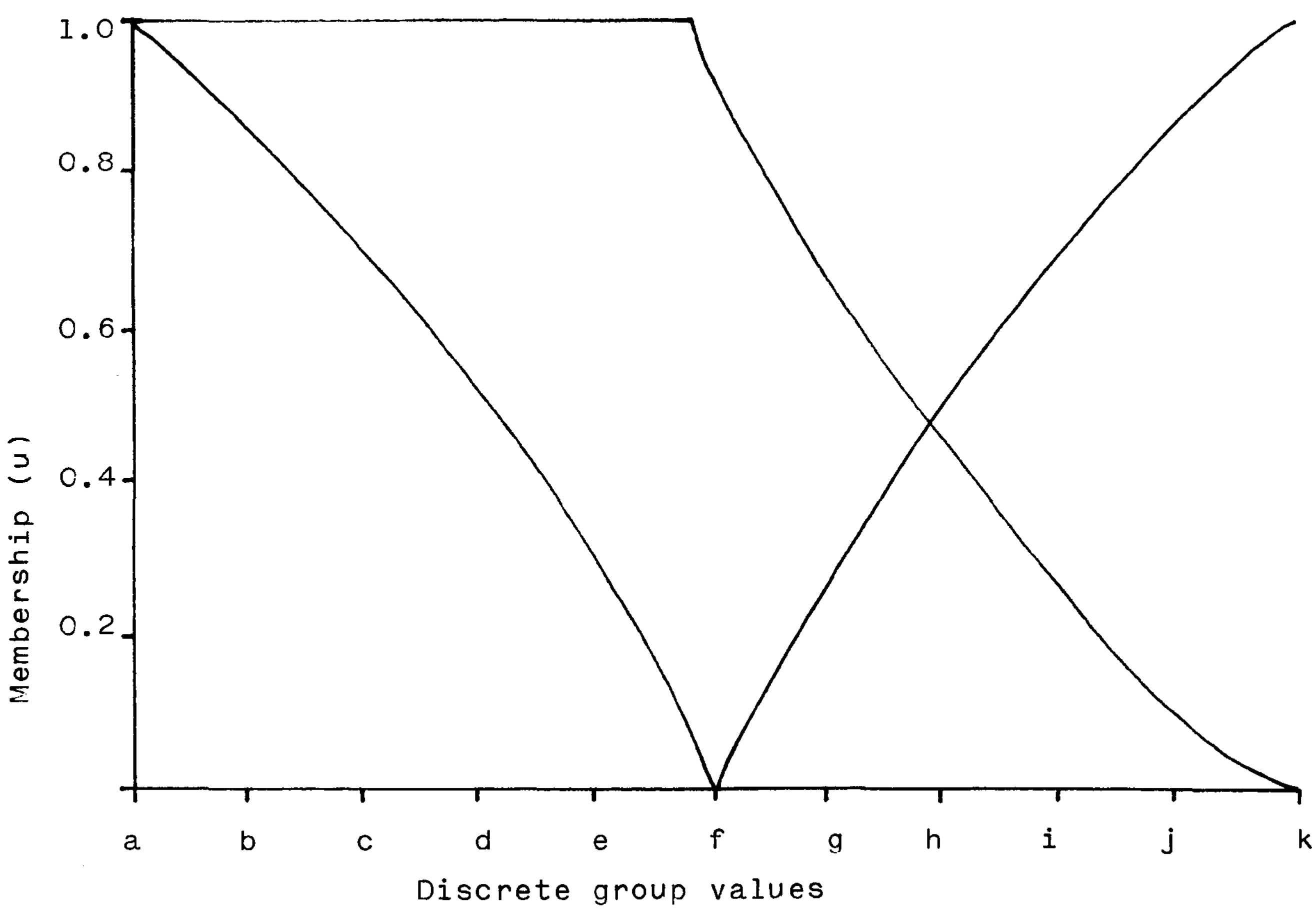
GENERALISED MEMBERSHIP FUNCTION TO ILLUSTRATE THE CONCEPTS OF "GENERALITY, AMBIGUITY AND VAGUENESS."



APPENDIX FIGURE 4c

MEMBERSHIP FUNCTION OF ANGULARITY AND ROUNDNESS AND 'NOT ANGULAR'.

(After Beddow, Philip and Nasta, 1980).



APPENDIX TABLE 4

EXAMPLE OF DETAILED FUZZY RESULTS
STORM 16.11.81, SAMPLE 2.

Feature	Particle															
	1	2a	b	4	5	6a	b	7a	b	c	8a	b	c	d	e	8B
A		4						2								
B	2		2	2	5		5	3	5	5	4	5	5			4
C		2		1				3	3		3	2				
D	3		4			5	1							5	5	2
E		2	4	3		4		2		1				5	3	2
F	1					5				1				2	4	1
G	5	2	3	3			2	4	3		2	4		3	4	3

APPENDIX 5

DETAILED SURFACE AREA RESULTS.

ROAD SEDIMENT

Particle	Total Number of Squares	Feature	No. Squares Feature	Feature % of Total Area
2A	2868	2	1897	66
		9	51	2
		10	680	24
		11	139	5
		12	129	4
		15	74	3
2B	3642	2	3181	87
		9	172	5
		18	289	8
4Aa	857	2	829	97
		9	9	1
		24	19	2
4Ab	1028	3	919	89
		5	4	0.5
		11	6	7
		18	74	2
		24	25	
4	6883	10	5664	82
		11	572	8
		12	98	1
		13	84	1
		14	40	0.5
		15	100	1.5
		17	8	0.1
		18	191	28
		24	126	2
1	3813	3	557	15
		5	141	4
		10	1737	44.5
		12	155	4
		15	289	7.5
		24	934	25
5	5214	2	4214	81
		10	668	13
		15	211	4
		24	121	2
7A	2691	9	2691	100
8A	1857	1	1687	91
		15	42	3
		24	128	6
8B	3739	2	3574	96
		9	16	0.4
		15	96	2.5
		24	53	1.4

AIRBORNE SEDIMENT

1	835	2	779	93
		9	317	38
		24	23	3
1A	4195	11	1501	36
		22	2358	58
		24	336	8
3	801	11	135	17
		12	345	43
		22	321	40
		24	135	17
5A	116	5	237	21
		10	802	72
		12	21	2
		15	12	1
		24	44	4
5B(i)	1370	22	1305	95
		24	65	5
5D	1544	2	1356	89
		9	176	11
		24	12	1
6A	521	22	510	98
		24	11	2
6B	2626	10	1628	62
		24	998	38
6C	1191	10	1144	96
		24	30	7.5
		9	17	1.5
6D	3712	10	3424	92
		15	8	0.5
		24	280	7.5
4B(i)	92	22	88	96
		24	4	4
4B(ii)	46	22	44	96
		24	2	4
4B(iii)	33	22	32	100

4B(iv)	26	22	26	100
5B(ii)	41	22 24	40 1	98 2
5B(iii)	28	22	28	100
5B(iv)	12	22	12	100
5B(v)	7	22	7	100
5B(vi)	18	22	18	100
5B(vii)	7	22	7	100
5B(viii)	25	22	25	100
5B(ix)	9	22	9	100
5B(x)	3	22	3	100
5B(xi)	22	22 24	21 1	95 5
5B(xii)	14	22 24	13 1	93 7
6A(ii)	563	22	563	100
6A(iii)	388	22 24	384 4	99 1
6A(iv)	250	22	250	100
6A(v)	225	22 24	220 5	97 3
6A(vi)	100	22 24	97 3	97 3
6A(vii)	100	22	100	100
6A(viii)	117	22 24	115 2	98 2
6A(ix)	64	22	64	100
6A(xi)	25	22	25	100
6A(xii)	25	22	25	100
6A(xiii)	31	22	31	100
6A(xiv)	21	22	21	100
6A(xv)	34	22	34	100

6A(xvi)	103	22 24	49 54	48 52
6A(xvii)	20	22 24	5 15	25 75
6A(xxiii)	24	22 24	19 5	79 21
6A(xix)	14	22 24	11 3	79 21

ROOF SEDIMENT

1A	4350	10 11 12 15 18	2724 30 20 29 1547	63 0.7 0.5 0.7 35
1C	2136	19 24	2123 13	99 1
1D	3298	10 24	2775 523	84 16
1E	3776	22 24	2656 1120	70 30
1F	2449	22	2449	100
3	2215	2 9	1817 398	82 8
3B	2590	19 24	2540 54	98 2
4C	3319	22	3319	100
5A	2024	2 7 9 10 11 21 12 13 17 24	826 40 57 425 9 26 85 85 22 450	41 2 3 21 0.5 1 4 4 1 22
5B	2713	2 7 8 17 18 22	1394 39 115 185 366 335	51 1.3 4 7 13 12

STORM SEDIMENT 5.5.81.

Sample 2

1	755	21 9 10 15 24	479 39 168 44 25	63 5 22 6 3
2	3047	4 10 15 18 24	326 2666 119 63 199	11 87 4 2 6.5
3	1669	2 4 15 18 24 10	123 325 35 47 398 1066	7 19 2 3 24 64
4	573	4 9	y54 19	97 3
5	750	2 4 24	695 750 55	93 100 7

Sample 10

2	8471	2 4 9 10 11 12 15 17 18 24	4690 1292 239 2276 46 16 358 200 99 547	55 16 3 27 0.5 0.2 4.2 2 1 7
3	5398	2 4 9 10 11 12 15 17 24	4163 400 288 227 9 12 196 205 208	77 7 5 4 0.2 0.2 4 4 6
5	2006	2 11 15 10 9	1074 23 56 904 40	51 1 3 43 2
4	1506	2 4 15 24 10 12 9	978 1320 116 126 343 15 271	65 88 8 8 23 1 18
6	1299	10 12 13 24 2	794 58 10 22 415	61 5 1 2 32
7	5840	2 4 9 10 11 12 15 17 21 24	4569 3548 318 494 14 20 193 80 20 134	78 61 5 8 0.2 0.3 3 1 3 2
9	1356	2 9 15 24	1331 86 38 61	88 6 3 4
9A	9725	2 15 24	1677 37 8	97 2 0.5
10	2863	2 4 9 10 15 24 17	1886 1749 60 332 65 71 429	66 61 2 12 2 3 15 18

Sample 18

1	3778	2 4 9 24 10	3525 2778 91 130 32	93 74 2 3 1
2	4316	4 6 24	4316 92 30	100 2 1

4	3637	2 4 6 12 15 13 24 10	2932 2712 150 41 111 39 32 382	78 74 4 1 3 1 1 10
4A	1933	2 15 24 10	236 68 31 1598	12 4 2 83
5	4851	2 4 10 15 24 8	3761 561 276 118 52 80	77 12 6 3 1 2
5A	4075	4 10 24	3422 559 94	84 14 2
5B	3130	8 4 10 12 15 24 2	47 35 488 36 40 92 2392	2 1 10 1 1 3 76
5C	3539	4 10 24 8 15	3242 147 81 66 3	92 4 2.5 1.5 0.1
6	1686	2 4 11 12 15 24 8	1449 1686 14 21 87 75 40	86 100 1 1 5 4 3
6B	1613	2 4 15 18 24 12 6	1308 1613 100 15 50 20 120	81 100 6 1 3 2 7
7	1045	2 4 8 10 15	955 67 81 90 19	91 6 2 9 2
7A	1015	2 4 10 8 15 13 24	789 1615 48 10 35 102 25 6	78 100 5 1.5 3 10 2.5 1

Sample 20

1A	494	2 4 10 11 12 15 18 24 8	35 3 379 2 13 11 5 19 27	7 0.5 77 0.5 2.5 2 1 4 5.5
1B	3022	10 11 12 15 16	2541 63 338 66 14	84 2 11 2 1
1C	2752	10 11 13 15 18 24 6	1556 30 125 70 843 128 20	56 1 5 3 30 5 1
1D	3278	6 10 12 15 18 24	77 2206 85 35 871 30	2 67 3 1 26 1
2A	3779	6 10 11 12 14 15 18 24	63 3229 12 7 14 63 330 61	1.5 85 0.5 0.5 0.5 1.5 9 1.5

2B	5974	6	31	0.5
		10	2763	46
		11	48	1
		15	86	1.5
		18	2989	50
		24	57	1
3A	3741	2	1543	41
		6	39	1
		10	1717	46
		11	32	1
		12	12	0.5
		13	17	0.5
		15	58	1.5
		18	180	5
		24	58	1.5
		8	85	2
3B	5465	10	1175	22
		11	51	1
		15	32	1
		18	4207	77
4A	3626	2	107	3
		10	537	15
		11	25	0.5
		12	78	2
		15	87	2.5
		18	2765	76
		24	27	1
5	2575	2	20	1
		6	38	1.5
		10	101	4
		11	7	0.5
		12	75	3
		15	65	2.5
		18	2275	88
7	2548	10	663	26
		11	29	1
		12	217	8.5
		15	52	2
		18	1559	61
		24	28	1.5
8	2719	10	724	27
		11	25	1
		12	75	3
		13	50	2
		14	35	1.5
		15	35	1.5
		18	1746	64
		24	29	1
9	3467	15	105	3
		18	3310	95.5
		24	52	1.5

Sample 36

1	4730	2	3763	80
		4	400	8.5
		6	37	1
		8	96	2
		10	357	7.5
		12	6	10
		15	86	2
		16	36	1
		18	257	5.5
		24	92	2
1A	1566	2	1237	79
		4	21	1.5
		6	148	9.5
		15	46	3
		24	47	3
		17	88	6
2	7968	10	2236	28
		11	39	0.5
		12	32	0.5
		13	238	3
		14	33	0.5
		15	79	1
		18	5257	66
		24	54	0.5
2A	1820	10	1166	64
		11	6	1
		12	36	2
		15	67	4
		18	485	27
		24	60	3
3	6668	15	73	1
		23	841	13
		24	58	1
5	4938	2	130	3
		10	2804	57
		15	146	3
		18	1752	35
		24	106	2
6	2361	10	1962	83
		24	399	17
7	3696	2	525	14
		8	61	2
		10	1479	40
		15	117	3
		17	1407	38
		24	107	3

8	3637	2	2947	81
		4	215	6
		8	59	2
		10	255	7
		15	212	6
		24	164	5
9	2537	2	2087	82
		8	120	5
		10	152	6
		15	47	2
		16	16	1
		24	115	5
10	2807	2	2388	85
		8	121	4
		10	68	2.5
		15	73	3
		16	10	0.5
		24	147	5
10C(i)	370	8	17	5
		10	317	86
		15	33	9
10C(ii)	643	8	53	8
		10	519	81
		15	50	8
		24	21	3

Sample 42

1	1142	2	1028	90
		15	44	44
		24	70	7
2A	8224	4	6750	82
		6	89	1
		10	421	5
		15	35	0.5
		21	229	3
		24	700	8.5
2F	3367	10	1300	38
		22	2067	62
2G	678	2	557	82
		10	75	11
		15	46	8
3	3765	2	1495	40
		4	1125	30
		15	430	12
		21	33	1
		24	97	3
		8	585	15

4	3630	2	2353	65
		8	600	17
		10	90	2
		15	459	13
		17	68	2
		24	60	2
4B	1677	2	461	29
		8	88	5
		10	976	58
		15	114	7
		24	38	2
5D	4653	2	4400	95
		4	1119	24
		8	27	1
		15	162	3
		24	19	1
		6	45	1
5	4219	2	2444	58
		4	300	7
		6	47	1
		8	500	12
		10	485	12
		11	28	1
		15	322	7
		17	250	6
		24	143	3

APPENDIX 6 .

BRICK AND TILE CLAY CONTROL STUDIES.

Building materials were seen as a substantial source of sediment in the catchment. Rainfall washes sediment off roofs and walls which is fed by gutters into the drainage system. To recognise this sediment as distinct from road and soil particles, some control sediment was examined. Particles were brushed onto a sample stub from weathered and freshly broken surfaces of both brick and roof tile.

The results for brick sediment can be seen in Appendix6, Plates 1 to 7 and the Fuzzy Analysis is given in Appendix Table 6. Fresh brick sediment is made up of a combination of features not previously associated with each other in this study. Aggregates or clusters of particles form the dominant mode of the sediment. Base particles (10 to 15μm) of fresh faced angular and vesicular surfaces support adhering fine fresh faced angular fragments 1 to 3μm. This sample appears to have been only slightly weathered because very little is recognised in the way of abrasion or solution and precipitation features.

From Appendix Table 6 it can be seen that tile material is also dominated by fresh faced angular particles with substantial development of impact features, presumably from the tile construction process. Plates Appendix6 1-7 provide the appearance of corroded or

APPENDIX TABLE 6

FUZZY ANALYSIS OF BRICK AND ROOF TILE SAMPLES.

Sample / Feature	Brick		Tile	
	μ	%	μ	%
A Aggregate@	4.0	71*	2.5	25
B Si Features	2.8	57	2.9	50
C Pitting	2.0	14		
D Fresh Face	4.7	100**	3.5	100**
E Angularity	4.7	86**	4.3	100**
F Steps	3.0	14	4.0	50
G Impact Pits	4.0	29	3.7	75*
H "Crinkles"	3.0	29	5.0	25
I Clays				

@ Feature list given in Table 7.3.

μ = Mean fuzzy value of feature from sample particles.

% = Percentage of particle with feature.

71* = Notable values, 70–79

100** = High values, 80–100.

pitted surfaces. Particles of 50 to 100μm are largely covered with fine fragments of approximately 3μm and small isolated pieces of precipitated material. The particles with features of precipitation and solution, and some degree of rounding, will have come from the outer weathered surface of the tile.

These samples are from only one area, of the catchment, in which one type of building materials were used. The composition and microtexture of the bricks and tiles will vary slightly across the catchment but the results of this study do permit the recognition of brick and tile particles in the surface and drain sediment samples.

APPENDIX 6

BRICK CLAY.

Plate 1 x 1700 Overall view of brick sediment.

Plate 2 x 4300 Detail of Plate 1, fresh-faced vesicular particle with adhering fine angular, fresh-faced fragments.

Plate 3 x 4300 Detail of Plate 1, precipitation solution surface; rounded particles and fibrous adhering particles (l.h.s.) angular abraded fresh particles (r.h.s.).

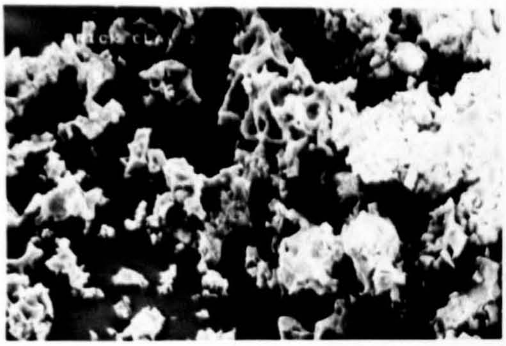
Plate 4 x 4300 Detail of Plate 1, fresh-faced angular particle; step feature; precipitate.

ROOF-TILE CLAY.

Plate 5 x 280 Overall view of large particles covered in fine fragments.

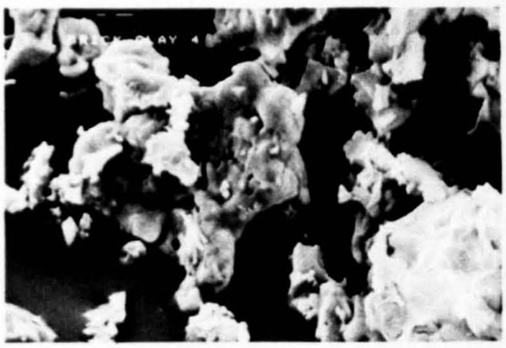
Plate 6 x 1700 Detail of Plate 5, solution areas and fine adhering fragments including precipitated material.

Plate 7 x 9100 Detail of Plate 5, solution surface (lower left), fresh-faced angular fragment with small area of precipitate (lower right).



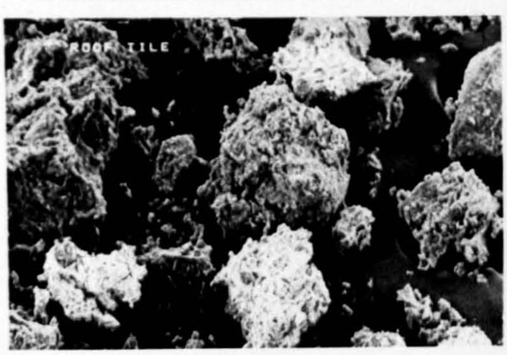
47μm

μm



20μm

20μ



29μm

2.5μm

1μm.

APPENDIX 7

THE PRESENCE OF HIGH FUZZY SCORES FOR STORM SEDIMENT.

STORM 16.11.81. GROUP I

Feature	Particles

Sample 2

A	2a
B	5 6b 7a b c 8a b c 8B
C	7a b 8a
D	1 2 6a b 8d e
E	2b 4 6a 8d e
E	5 8e
G	1 4 6b 7a b 8b d e 8B

Sample 5

A	4
B	3 4 5 6 7c 8b c 10a c 12a b c
D	6a b c d 7a b 8a
E	4

Sample 8

B	7 8a 10b c 11a 14a c
C	8a 10c 11a
D	8a b 9a b 13a b 14b
E	8a 9b 11b 13a b 14b c
F	9a 11b
G	7 9a 10c 11b 13a

Sample 11

B	2b 4 5 6 12b c d 13a b c d 14c
D	1 2a 3 4 5 9 10 11a 12a b c d 13a b c d 14a b
E	1 2a 3 4 5 9 10 11a 12a c 13a b c d 14a b
F	9 10 14b
G	4 5 9 13a b c d

Sample 14

A	10a
B	1 3a b c d e 4 5a c 7a 8a 10a b 12b c
D	2 3b e 5a b 6 7b 9 11 12a b 13a b c 14
E	1 2 3b c d e 5a b c 6 7a b 8a 9 11 12a b c d 13a b c 14
F	2 10a
G	1 2 3a b c d e 5a 6 7a b 8a 9 11 12b c 13a c

Sample 17

A	2b 10
B	2b 3a 4a c 5b 10 12c 13 14
D	3b c d 4a b d 5b c 6a b 11b 12c
E	2a b 3a b c d 4a b d 5a b 6a b 10 11b
F	3c 4b
G	2a 3c d 4a 4c 6b 10 11a

Sample 20

A	2 3a 4b 5b
B	1b c e g h 3c 4a b 7a b 8a 9b 10a
Ç	1c e g h ab 10a b
D	1d 2 3a b 5a b 7a b 9a 10b c
E	1a b c d f 2 3a b 5a 7a b 8a 9a 10c
F	7a b 9a 10c
G	1c f 2 3a 5b 7a b 9a
J	4a

STORM 17.11.81. GROUP I/II

Sample 2

A	7 9a 13
B	2a 4a b c 5 7 8a 9b d 10a b 11a b 12 13 14
D	2b 4c 8a b 9c 11a 13 14
E	2b 4c 7 8a 9 b c d 10a b 11a
G	2b 4a b 5 7 9a b 11b

Diatom

Sample 8

A	6 9 12
B	2 5c 6 9 11 12 13
D	5b d 10
E	5c b d 6 9 13
F	5b
G	5c 6 13
I	1 2 4 5a

Sample 16

A	3 4b 5 13 14
B	1 3 4b 5 6 7a 8c 9 10a 11 12a 13 14
D	2 4c 7b 8a b 10a b 12b 13 14
E	1 4a b c 7a b 8a b c 10b 12a b 14
F	2 7b 10b 12b
G	2 4a b 7 7a b 9 10b

Sample 25

A	3 4 12
B	1b 2a b 3 4 5a 6 8a d 9b c d e 10 11b d 12 13a 15b
D	1a 8a c 9f 11a c d e 13a 15a
E	1b 2a 3 4 5a b 6 8a 9b c d e f 11a c e 13a 15a
G	1b 2a b 3 4 5a b 6 8a b 9b d e 11d 13a b 14

Sample 32

A	6 10 11
B	1 5 6 8a 10 13 14 15b d 16a 17b
D	1 8b 10 12 15a c 16b
E	6 8a b 10 11 12 15a b 16a b
G	5 6 8a b 11 15 b 17a b

Sample 40

A	6 12
B	3a b 4a 6 7a 8 9a b d 10 11 12 13a b 14a
D	2 4 6 7c 8 9a b c 12 13c 14b
E	2 3a 4b 7c 8 9a b c 11 13c 14a b
G	2 3a b 4b 6 7c 8 9a b 12 13a 14a b

STORM 10.10.80 GROUP II

Sample 7

A	1a 2c 3a d 4 5
B	1a 2c 3a c d 4 5
C	3a c d 4 5
D	1b 2a b 3b
E	1b 2a b 3d
F	1b 2b
G	5

Sample 15

A	3 4 5
B	3 4 5
C	4 5
D	3
E	3

Sample 23

A	1a b 2 3 5b 6a 6 7
B	1a b 2 3 4a 5b 6a b c 7
C	1a b 2 3 5a b 6b c
D	1c 4b 6d
E	1c 5a 6d
F	1c
G	

Sample 31

A	1a b 2a b 3a b 4a b
B	1a b 2a b 3a b d 4a b
C	1a b c 2a b 3a b 4a b
D	1c 3c d
E	1c 3c d
F	1c 3 b c d

Sample 39
A 1b d 2a 3a b c 4 6a
B 1a b d 2a c 3a b c 4 6a c
C 1b d 2c 3a b c 4 6c
D 1a c 2a b 6a b c d
E 1a c 2a b c 6a b c d
F 2a b c 6a b c d
I 1c 6c

Sample 47
A 1a b 4d
B 1a b c d 2a 3a 4a b c d 5 a b
C 1c d 2a b c 3b 4 c d 5a b 6b c
D 1c d 2a b c 3b 4c d 5a b 6b c
E 1c d 2a b c 3a b c 4d 5a b
F 2a b 3a b
G 1c d 2a b c 3a b c 4c d 5a b

STORM 14.11.80. GROUP III

Sample 1
A 1 3a
B 1 3a b c 4a b
C 3a b c
D 3d 4b
E 3d 4b
F 3d
G 3d 4a b

Sample 8
A 2 3 4 6
B 1 2 3 4 6
C 1 3
D 1 6
E 1 6
G 2 4 6

Sample 16
A 2 3 5c 6a b
B 2 2a b d d e 3 4a 5c 6a b
C 2a d e 4a 6a b
D 2 3 4b 5a b
E 2 3 4b 5a 6a b
F 5a
G 2 3 4a b 5a 6

Sample 26
A 1 2a 5a
B 1 2a 3 4 5a
C 1 2a b c 3 4
D 1 2c 5a b
E 1 2c 3 4 5a b
F 3 5a
G 1 2a b c 5 5a

Sample 32
A 1 3 6b
B 1 2a 3 4a b 6a b c
C 1 2a 4a
D 2b 4b 5 6d
E 2b 5 6c d
F 2b 4b 5

Sample 46
A 2 3 4
B 2 3 4
C 1a v 2 3
D 1a b 2 3
F 1b 2 3
I 2 3

STORM 26.11.80. GROUP IV

Sample 4
A 3 6c 7b
B 1a b c d e 2a 3 4a b c d 6a b c 7a b d
C 1c 3 4d 6b 7a c d
D 1e 2b 4 5
E 1e 2b 4d 5 7a c
H 4a

Sample 9
A 1 3 5
B 1 2a b c 3 4 6
C 1 3
D 4
E 2a b 4
G 2b c 3

Sample 16
A 6
B 3a b 5 6
C 3a b
D 5
E 5
G 3a b

Sample 25
A 4a 5f 6b
B 3a b 4a 5a b c d e f 6b 7a b c d e
C 6b 7b
D 3a 4a b c 5c 7a d e
E 3a 4a b c 5c d e 7a b c d e
F 7a
G 3a 4a 7a
F 7a
G 3a 4a 7a
I 6a

Sample 34
A 1a 2a 3a 4
B 1a b c 2a b 3a c 4
C 1a b c 2b
D 1a d e f 2a 3b c d
E 1a d e f 2a 3a b d
F 1d 2a
G 1c 2a

Sample 40
A 1h
B 1a b c f h
D 1a c d h
E 1a d e h

APPENDIX 8

FLUME PARAMETERS.

Capacity of Flume System + Flume (including header tank) and Receiver Tank + Pipes.

Total Water Volume

Flume (including header tank)

length : 2.50m

width : 0.15

depth : 0.09

$$\text{Volume} = 2.50 \times 0.15 \times 0.09$$
$$= \underline{0.034m^3}$$

Receiver Tank

length : 0.89m

width : 0.36

depth : 1.07

$$\text{Volume} = 0.89 \times 0.36 \times 1.07$$
$$= \underline{0.342m^3}$$

Pipes (full)

(a) length : 2.3m

diameter : 0.17m

$$\text{Volume} = \pi \times (0.085)^2 \times 2.3$$
$$= \underline{0.052m^3}$$

(b) length : 2.2m

diameter : 0.15m

$$\text{Volume} = \pi \times (0.075)^2 \times 2.2$$
$$= \underline{0.039m^3}$$

Total Volume Pipes = 0.052 + 0.039

$= \underline{0.091\text{m}^3}$

Total Water Volume = 0.034 + 0.342 + 0.091

$= 0.468\text{m}^3$

$= \underline{468\text{l}}$

Sediment Concentration.

Weight of Sediment = 250 000mg

Volume of Water = 468l

$$\text{Sediment Concentration} = \frac{250\ 000}{468}$$

$= \underline{534\ \text{mg/l}}$

Discharge.

Water level difference in manometer,

$l = 170\text{mm}$

Angle of inclination of manometer,

$\Theta = 55^{\circ}$

$Q = 0.604\ (l \sin \Theta)^{1/2}\ \text{l/s}$

$= 0.604\ (170 \sin 55^{\circ})^{1/2}$

$= \underline{7.13\ \text{l/s}}$

Velocity.

Average Velocity in flume

$$= \frac{\text{discharge}}{\text{cross sectional area of flume}}$$

$$= \frac{0.00713\text{m}^3\text{/s}}{0.09 \times 0.15\text{m}^2}$$

$= \underline{0.53\text{m/s}}$

APPENDIX 9

AN ATTEMPT TO SIMULATE THE SEDIMENT RESPONSE TO ABRASIVE WATER TRANSPORT.

A drain sample was subjected to ultrasonic bath treatment for selected time intervals in a crude attempt to recognise the time taken to produce the observed features created by drain flow.

To minimise the variables involved the drain sample chosen was from the top of the catchment where the sediment was generated within the immediate hectare. The distance of drain transport to the next access point was 22.0m and sediment features found there were compared with those produced experimentally. If the experiment was successful it was hoped to relate the forces generated in the bath to the distance travelled and possibly indicate the force effect of the processes at work in the drain, a significant gap in the literature.

Two drain subsamples, I and II, were subjected to ultrasonic bath treatment as follows; I : 5, 10 and 20 minutes, and on a finer scale, II : 2, 5 and 10 minutes.

An untreated sample was examined under the scanning electron microscope and used as a control in comparison with scanning electron microscopy analyses of each treated sample. The results are given in Chapter 9.